RI/RD 95-183

Final Report

Rocket Engine Combustion Devices Design and Demonstration Program

September 1995

by

Rockwell International

Rocketdyne Division

prepared for

National Aeronautics and Space Administration

Marshall Space Flight Center

Contract No. NAS8-39567

Alberto Duarte, COTR

Initiated under Air Force Phillips Laboratory

Contract No. F04611-89-C-022

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FOREWORD

This report describes work accomplished in the Rocket Engine Combustion Devices Design and Demonstration (RECDD&D) Program. It was part of the overall Advanced Launch System (ALS) Program, later redesignated the National Launch System (NLS). The contract was initially issued by the Air Force Astronautics Lab (AFAL) to Rocketdyne, a division of Rockwell International Inc., under the Advanced Development Program (ADP) contract F04611-89-C-022. Program direction was provided for the AFAL by Mr. Don Penn who was later followed by Mr. Bruce Farner. In June of 1991, the contract was transferred to NASA-MSFC control, and was designated contract number NAS839567. The NASA MSFC Contracting Officer's Technical Representative was Mr. Alberto Duarte. The Rocketdyne team was headed by Jim Lobitz as Program Manager. Mr. James McKinnon prepared the final report. The period of performance was from May, 1989 to October 1992.

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1.0 INTRODUCTION AND SUMMARY

INTRODUCTION

The objectives of the ALS Combustion Devices ADP were to demonstrate design and manufacturing technologies which would maximize component reliability while minimizing the cost of fabricating those components.

In response, the ALS (subsequently identified as the National Launch System, NLS) program was initiated with the goal of developing a new, low cost 580 klb thrust class Space Transportation Main Engine (STME), and a 640 klb thrust class Space Transportation Booster Engine (STBE). The STME would use liquid hydrogen as the fuel while the STBE would use liquid methane. Both engines would use liquid oxygen as the oxidizer.

In May of 1989 Rocketdyne started work on the contract to design, fabricate and test two liquid hydrogen thrust chamber and gas generator assemblies, and three workhorse gas generator assemblies. The thrust chamber included an injector, combustion chamber, nozzle and ignition system. These components were to demonstrate the basic reliability, operability and cost objectives of the NLS program. This report documents the results achieved on that contract.

SUMMARY

The Phase I portion of the Combustion Devices ADP progressed through concept selection and preliminary design of a liquid oxygen / liquid hydrogen thrust chamber, two gas generators, and a common ignition system. Detail designs were completed for various components. These include the injector body and combustion chamber castings as well as both the workhorse and prototype gas generators. Design activity for these components was conducted using the DoD Total Quality Management Guide. A Concurrent Engineering Team was utilized for each component. To aid in their design efforts, several TQM tools were used including Quality Function Deployment (QFD) studies of interconnect devices and combustion chamber jacket features; Pugh Concept Selection studies of combustion chamber design features; Taguchi studies of nozzle flow field interactions and Vacuum Plasma Spray (VPS) parameters; and a CPI study to improve the design process itself.

Low cost fabrication studies were performed in the areas of vacuum plasma sprayed (VPS) NARloy-Z for the combustion chamber and hypervelocity sprayed (HVS) Inconel 625 for the nozzle. Both fabrication technologies showed promise but still had technical problems to overcome at the end of their investigation. The injector low cost investigation was to test four subscale injectors with different element densities to determine the lowest number of elements that would produce acceptable performance. The four injectors were fabricated but not tested due to program restructuring.

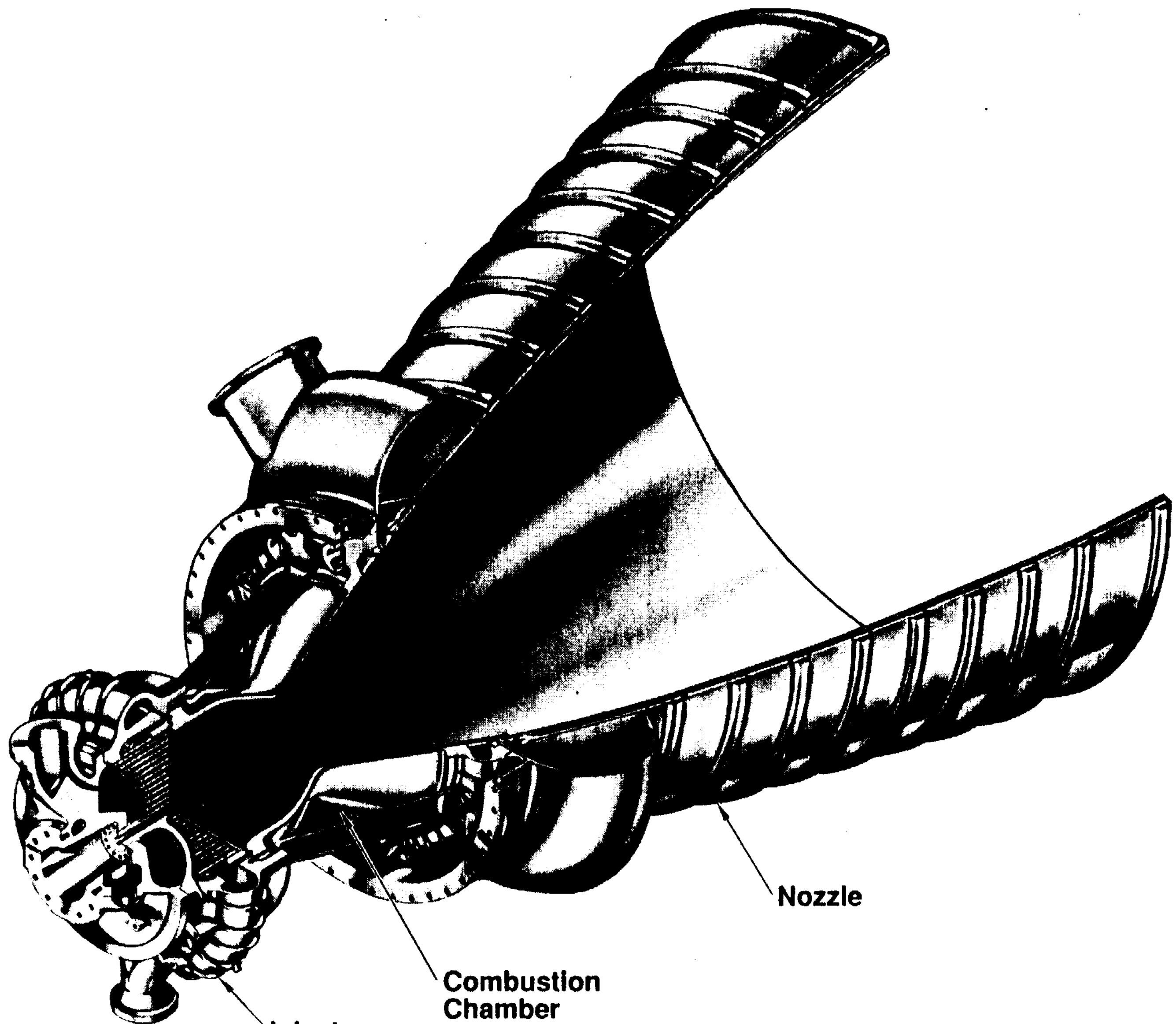
To aid in developing the lowest cost yet highly reliable component designs, two methodologies were developed. The first was a component cost model , which was cost estimation software created in a spreadsheet program and used throughout component design. The program is a very versatile, thorough cost predicting model and features a user friendly interface. A generic "cost model architecture" user manual was delivered which allowed other companies to estimate costs of other components. For designing high reliability into the hardware, a "design for reliability" methodology was also developed, in conjunction with government experts, and employed during the program.

The program was subsequently replanned with work on this contract focusing only on the combustion chamber due to a teaming arrangement between various engine contractors. During this period technology summary briefings were held for the injector (of which Gencorp Aerojet now had responsibility) and for the nozzle (for United Technologies Pratt & Whitney), both of which were held in January, 1991. The combustion chamber development team completed a new concept review which was held on July 12, 1991 to ensure that the design was the best that the new contractor team could produce. On the hardware side, the aft manifold and full combustion chamber jacket mockup castings were successfully produced out of JBK-75. The combustion chamber jacket was the largest aerospace quality vacuum investment casting ever produced at that time. At program end only minor casting development

problems still remained. As for VPS NARloy-Z, development continued with some success but significant development issues still remained.

Immediately following are charts that summarize the design features and results of each of the components worked on this program. Since cost was a major goal to this program, final cost estimates are also included for each of the major thrust chamber components versus their target costs.

Thrust Chamber Assembly



THRUST CHAMBER DESIGN CONDITIONS

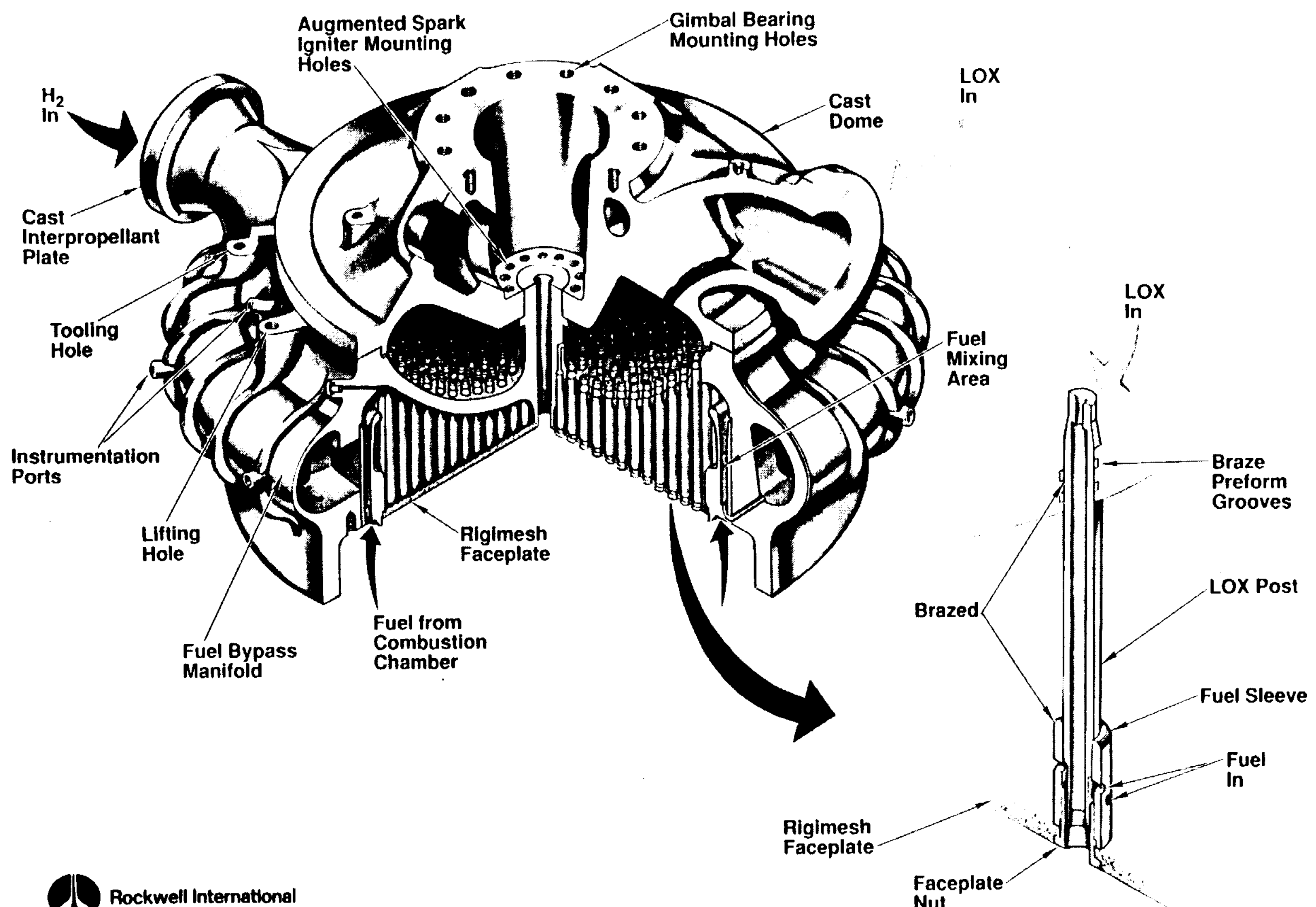
• Propellants	LOX/H^2
• Thrust	580K
• Combustion chamber diameter	21.00 inches
• Oxidizer flowrate	1132.36 #/sec
• Oxidizer temp	190°R
• Fuel flowrate (coolant & bypass)	163.96 #/sec
• Fuel temp (mixed)	183°R
• Mixture ratio (thrust chamber)	6.906
• Chamber pressure (nozzle stagnation)	2356 psia
• Maximum oxidizer inlet pressure	2864 psia
• Maximum fuel inlet pressure	2737 psia
• Injector Delta P oxidizer	16%
• Injector Delta P fuel	10.5%
• Cycle life	15 starts
• Factor of safety ultimate	1.5
• Factor of safety yield	1.1

* Sized for 105% power level

TECHNICAL APPROACHES IDENTIFIED

- Turbine gas-cooled nozzle
- Vacuum plasma spraying (VPS) of copper alloy for coolant circuit closeout and/or hot-gas wall
- Investment cast structural components
- Electrodeposited nickel cobalt (EDNi-Co) alloy for structure and coolant circuit closeout
- Electrodeposited copper-silver (EDCu-Ag) and dispersion strengthened copper for increased range of applicability and/or an alternative to wrought and VPS NARloy-Z
- Hypervelocity, oxy-fuel metal spraying (HVOF) for structural components

Injector Assembly



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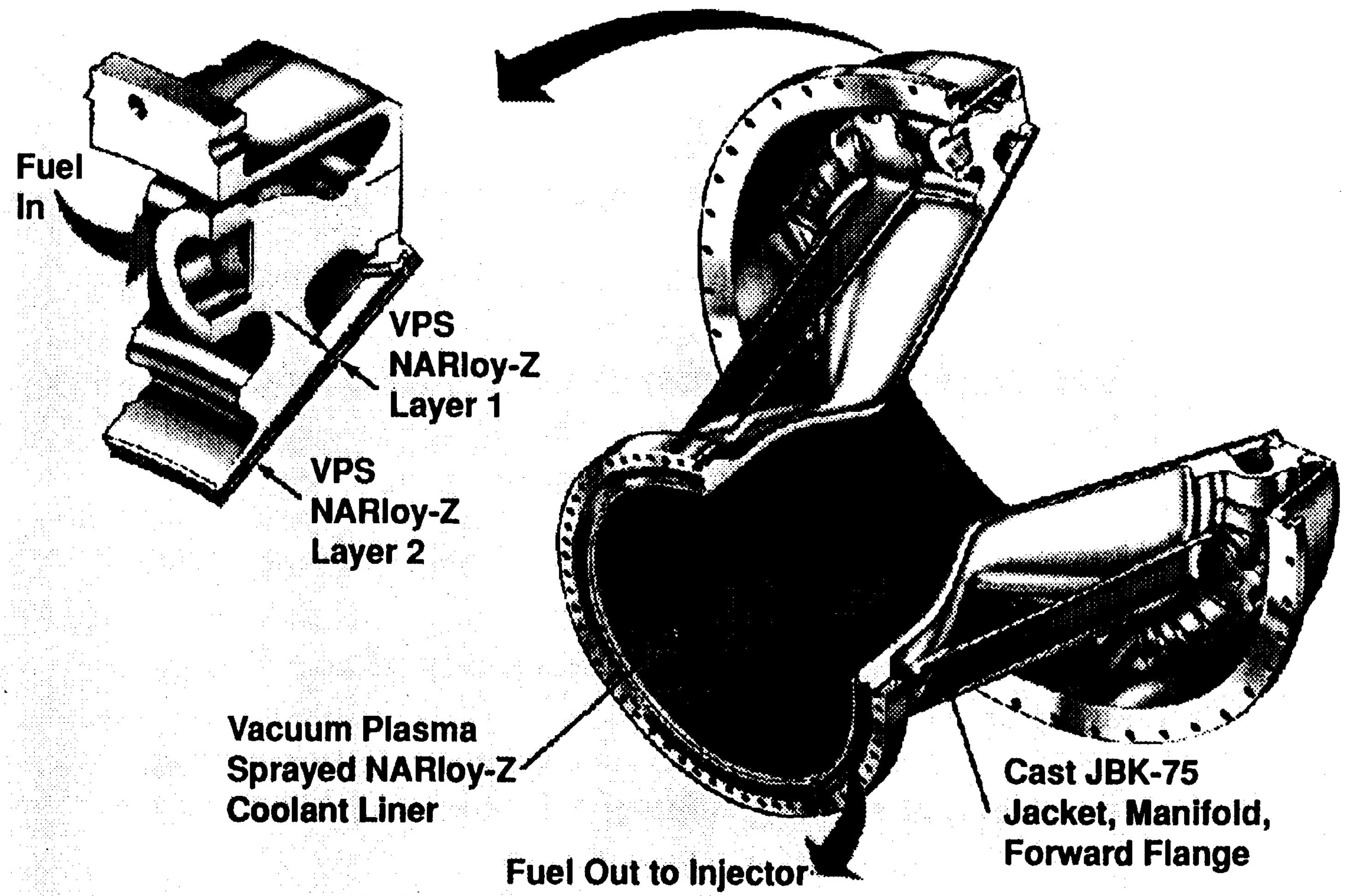
MAIN INJECTOR DESIGN FEATURES

- 550 coaxial elements
- Brazed element construction
- Cast fuel manifold and LOX dome structure
- Rigimesh faceplate
- Capability for adding acoustic cavity
- Single LOX dome inlet
- Single fuel feed manifold
- Bolt-on ignition system

MAIN INJECTOR RESULTS

- Completed Preliminary Design Review and detail drawing of fuel manifold/body
- Nearly completed design and analysis of LOX dome
- Fuel mixer concept designed and analyzed
  - Final mixer not selected/detail analysis not complete
- LOX post swage process tested and report written
- Four subscale injectors design and fabricated
  - Proof and leak testing required
- Injector summary report completed

COMBUSTION CHAMBER



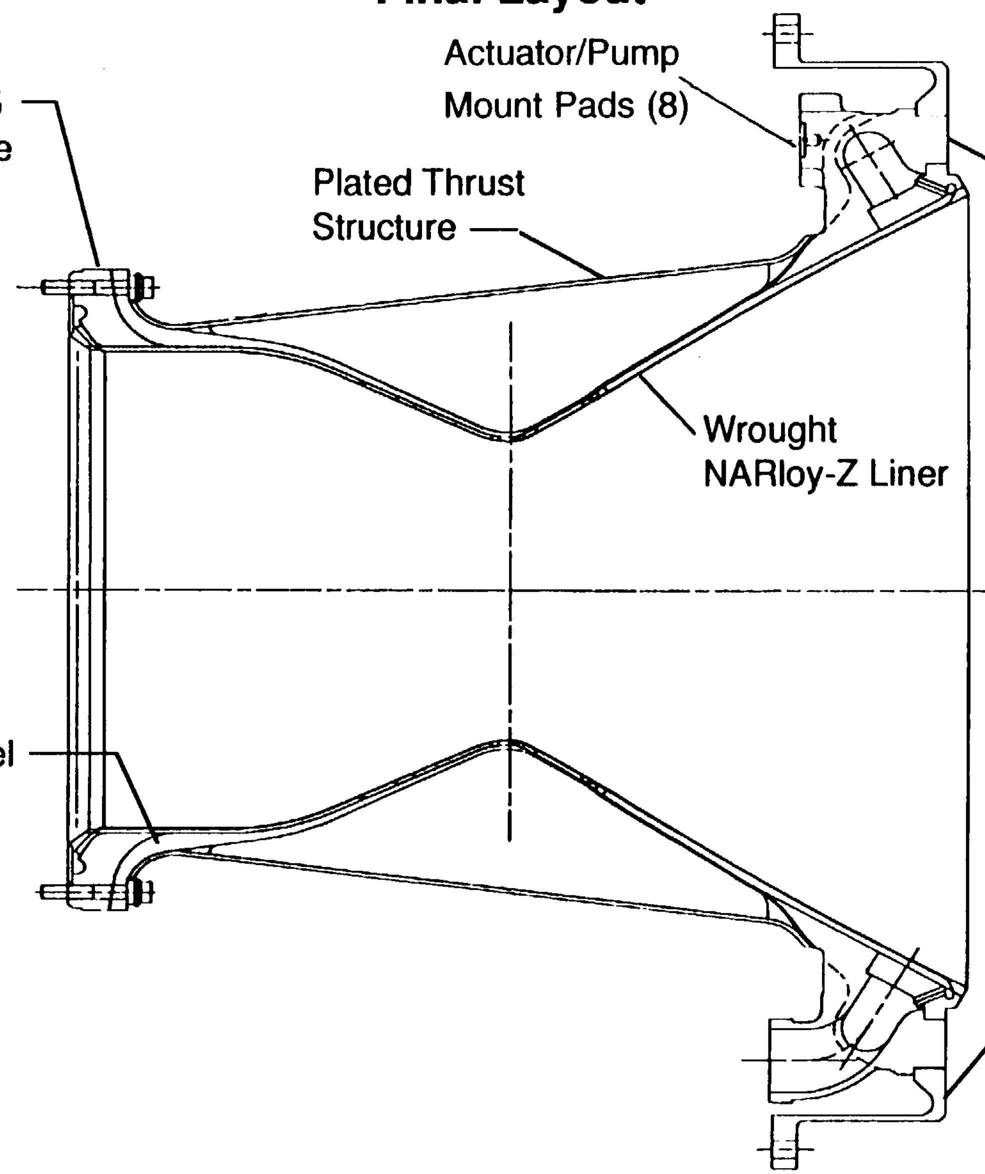
LC91C-30-3

VPS COMBUSTION CHAMBER DESIGN FEATURES

- Integral cast JBK-75 structural jacket
- 1-piece nozzle flex ring
- Wrought JBK-75 fuel manifold closeout ring
- HIP'ed NARloy-Z powder liner cold wall
- Vacuum plasma sprayed (VPS) NARloy-Z liner hot wall

LIDB/EDNi Co COMBUSTION CHAMBER

Final Layout



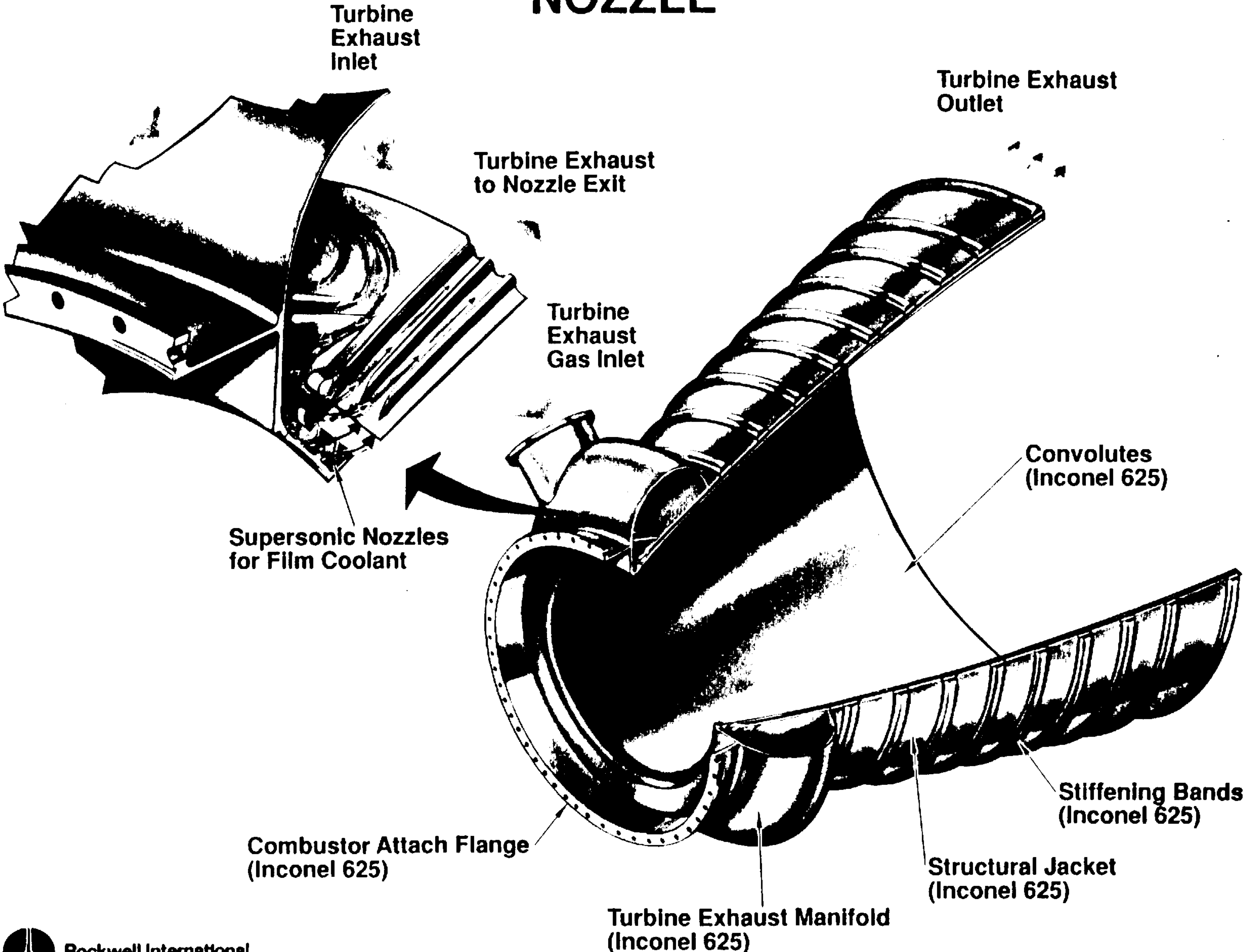
LIDB COMBUSTION CHAMBER DESIGN FEATURES

- **Cast JBK-75 fuel manifold**
- **Wrought JBK-75 fuel manifold closeout ring and forward flange**
- **Wrought NARloy-Z liner**
- **Forward flange and fuel manifold brazed to liner**
- **Electrodeposited Nickel Cobalt structure**
  - Liner closeout/pressure vessel
  - Structural stiffening shell

COMBUSTION CHAMBER RESULTS

- **Preliminary design and analysis of two concepts**
  - Liquid interface diffusion bonded (LIDB) liner with electrodeposited nickel-cobalt (EDNiCo) structure
  - Vacuum plasma sprayed (VPS) liner with full cast jacket
- **Produced large structural castings**
  - Cast JBK-75 exhibited very good properties with excellent castability and weldability
  - Aft manifold casting passed production NDE
  - Integral jacket was largest aerospace-quality vacuum investment casting produced to date
- **Significant VPS NARloy-Z copper alloy development results**
  - Preliminary properties obtained
  - Many process parameters identified

NOZZLE



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NOZZLE DESIGN FEATURES

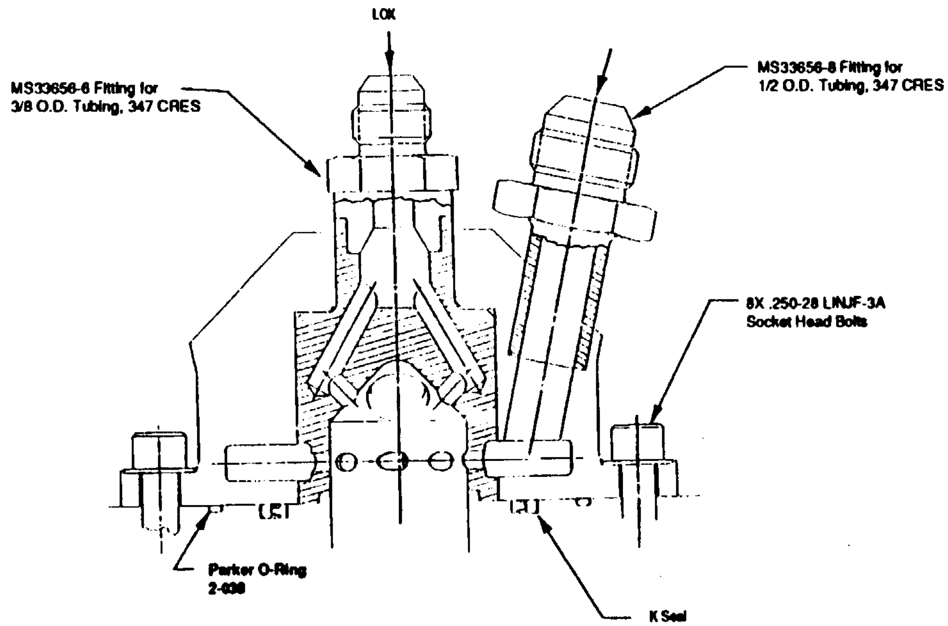
- Turbine exhaust film cooling
- Convoluted sheet metal liner
- Integral cast manifold flanges and combustion chamber flex ring
- Sheet metal exhaust manifold shell and inlet tube
- Sheet metal jacket panels and hat bands
- Liner laser welded to jacket panels

NOZZLE RESULTS

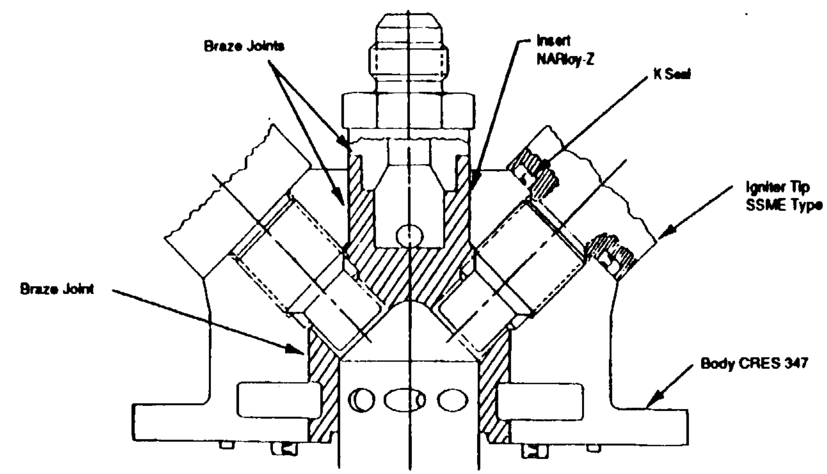
- Nozzle concept selection completed
- Film cooling Taguchi analysis completed
- Film cooling water table testing conducted
- Preliminary design and analysis of nozzle components
- High velocity spray (HVS) samples completed and analyzed
- Nozzle summary report completed

PROTOTYPE IGNITER ASSEMBLY

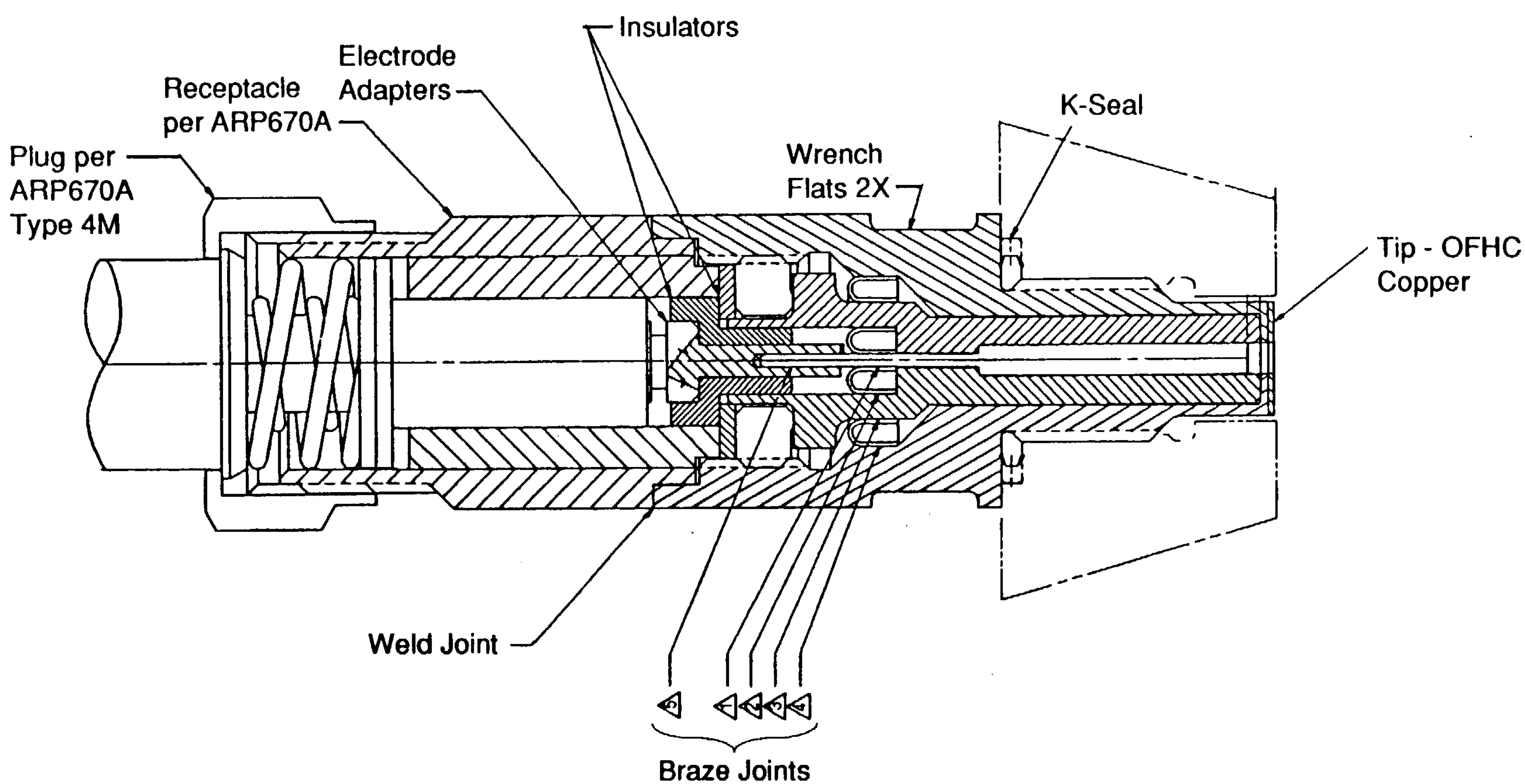
Propellant Feed Section



Igniter Mount Section



IGNITER SPARK PLUG ASSEMBLY



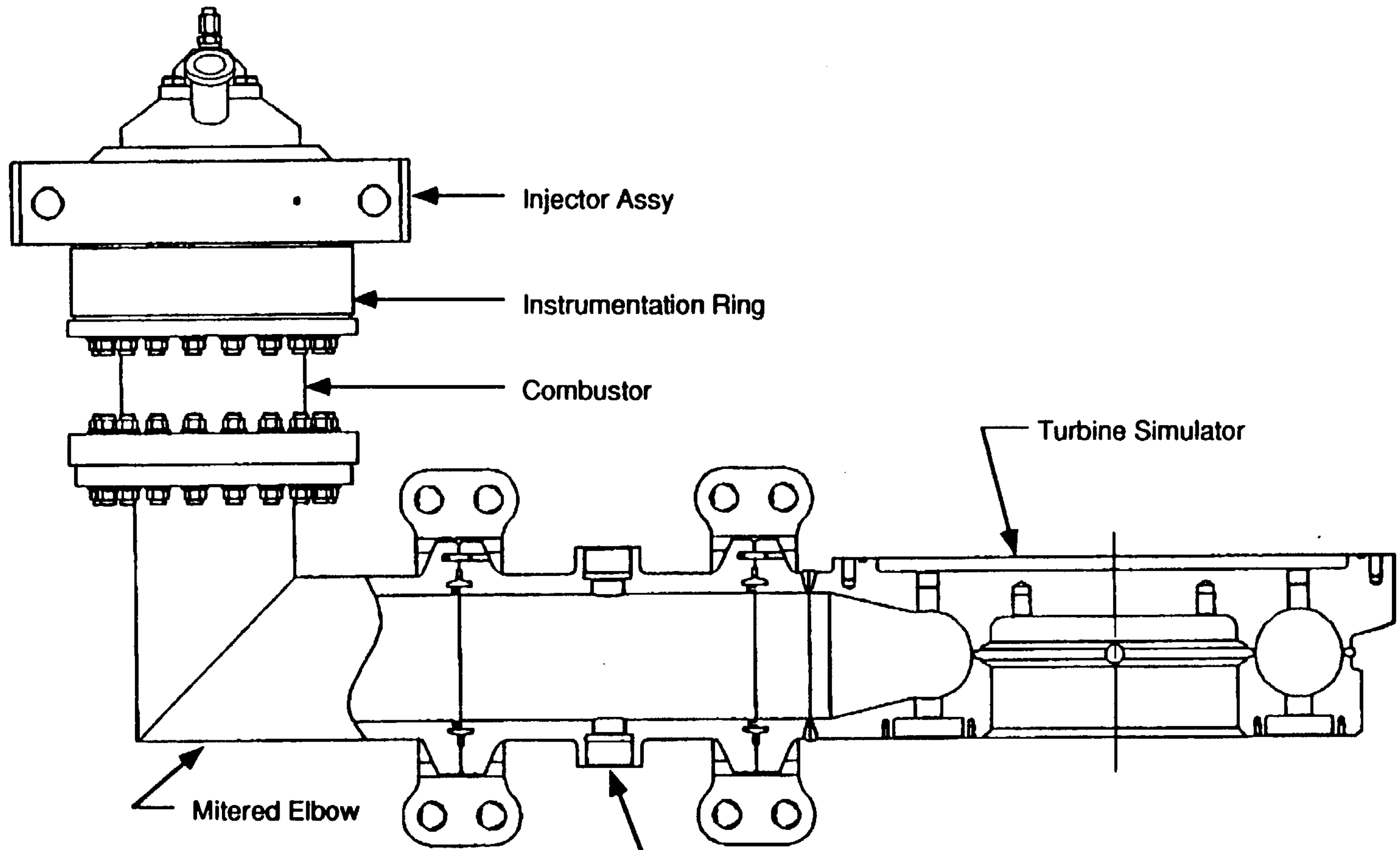
IGNITER DESIGN FEATURES

- **Augmented spark-torch igniter (ASI) system**
- **Bolt-on housing for ease of fabrication and replacement**
- **Simple brazed housing assembly**
- **Surface gap igniter plug (identical to plug used on SSME)**
- **Separate medium energy, high tension, capacitor discharge electronics**
  - Lower cast than integrated electronics/plug used on SSME
  - 40 sparks/second
  - 90 mj/spark at plug
  - Spark monitor circuit
  - Damage free operation with sparks quenched or spark cable shorted

IGNITER RESULTS

- **Detail design review completed of housing details and assembly**
- **Completed detail drawings of housing assembly**
- **Design of spark plugs completed**
- **Electronics specifications written and released**
  - Spark igniter (RC2074)
  - High voltage cable (RC2075)
  - Ignition Exciter (RC2076)

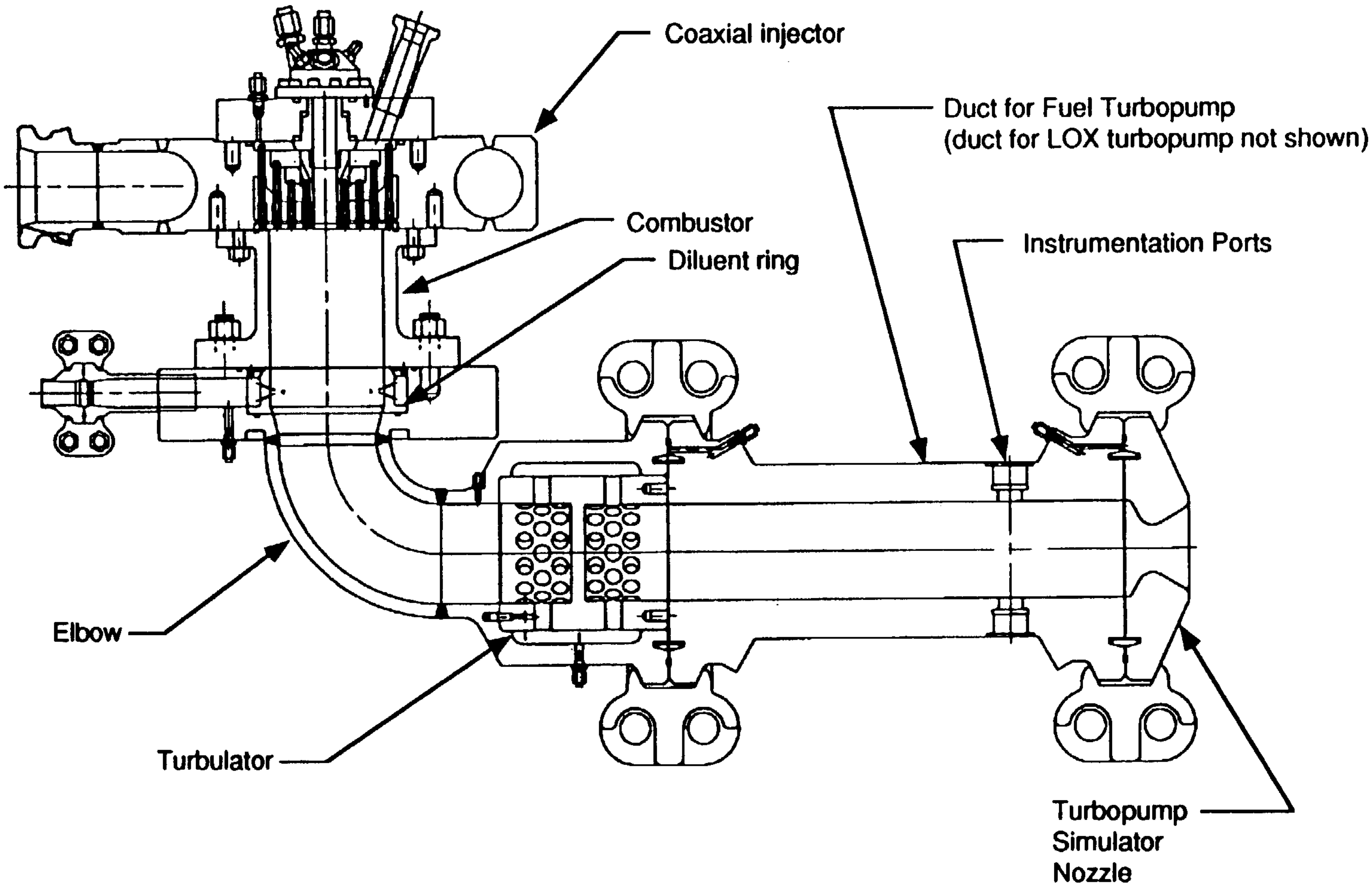
PROTOTYPE GAS GENERATOR ASSEMBLY



PROTOTYPE GAS GENERATOR RESULTS

- **Three injector designs completed**
  - Inclined fan
  - Coaxial
  - Box pattern
- **Detailed design and analysis of all hardware completed**
  - Instrumentation ring
  - Combustor
  - Elbow
  - Instrumentation spool
  - Turbine simulator
- **Detailed drawings of all hardware released**

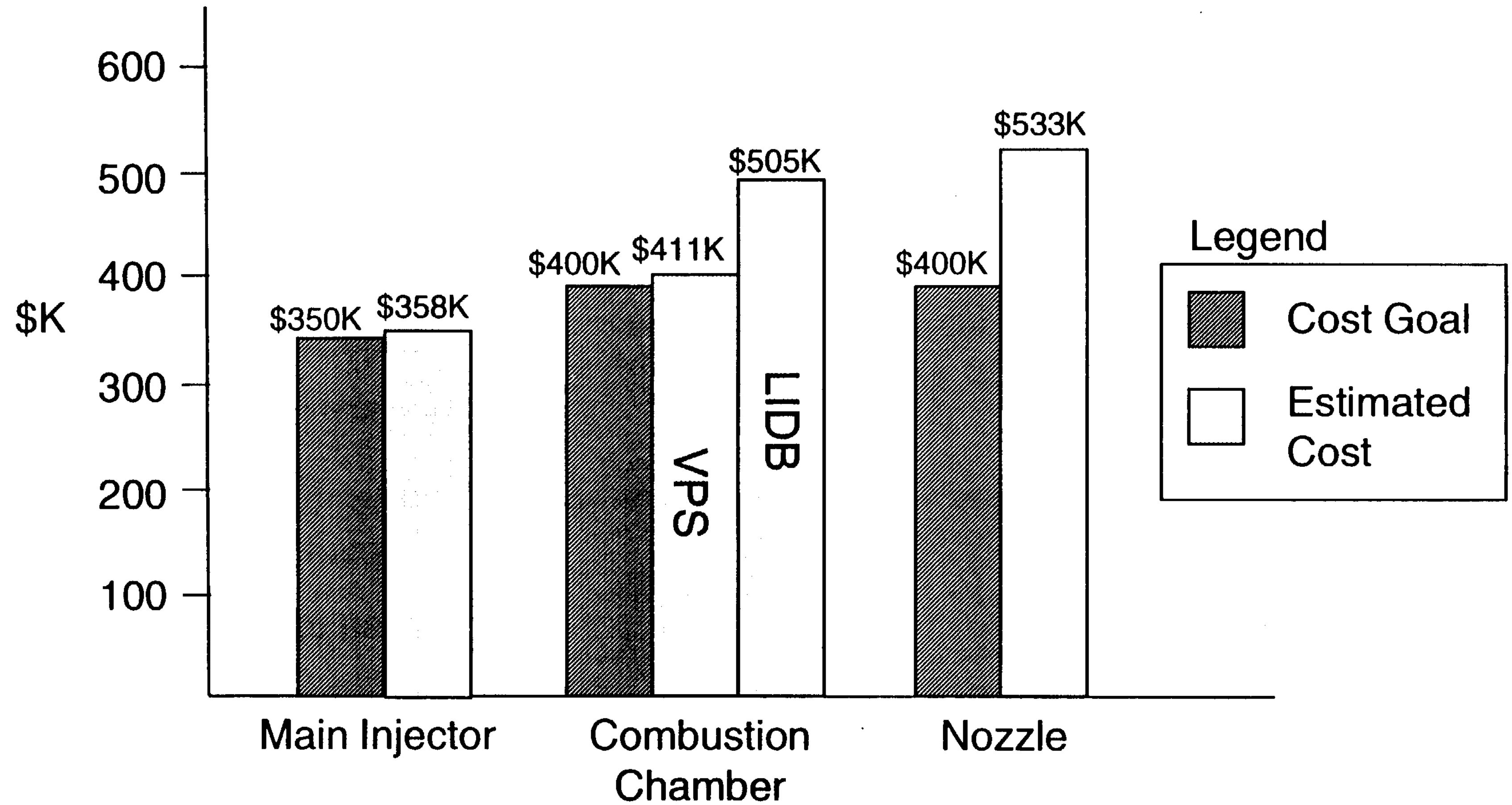
WORKHORSE GAS GENERATOR



WORKHORSE GAS GENERATOR RESULTS

- **Facility interface control document (ICD) completed**
- **Detail design and analysis of all hardware completed**
  - Injector assembly
  - Combustor
  - Elbow
    - Diluent ring
    - Turbulator
  - LOX and fuel turbopump ducts
  - Turbopump simulator nozzles
- **Detail drawings of all hardware nearly completed**

SUMMARY OF COST ANALYSIS
(Major Components)*



* Latest available 500th unit cost estimates

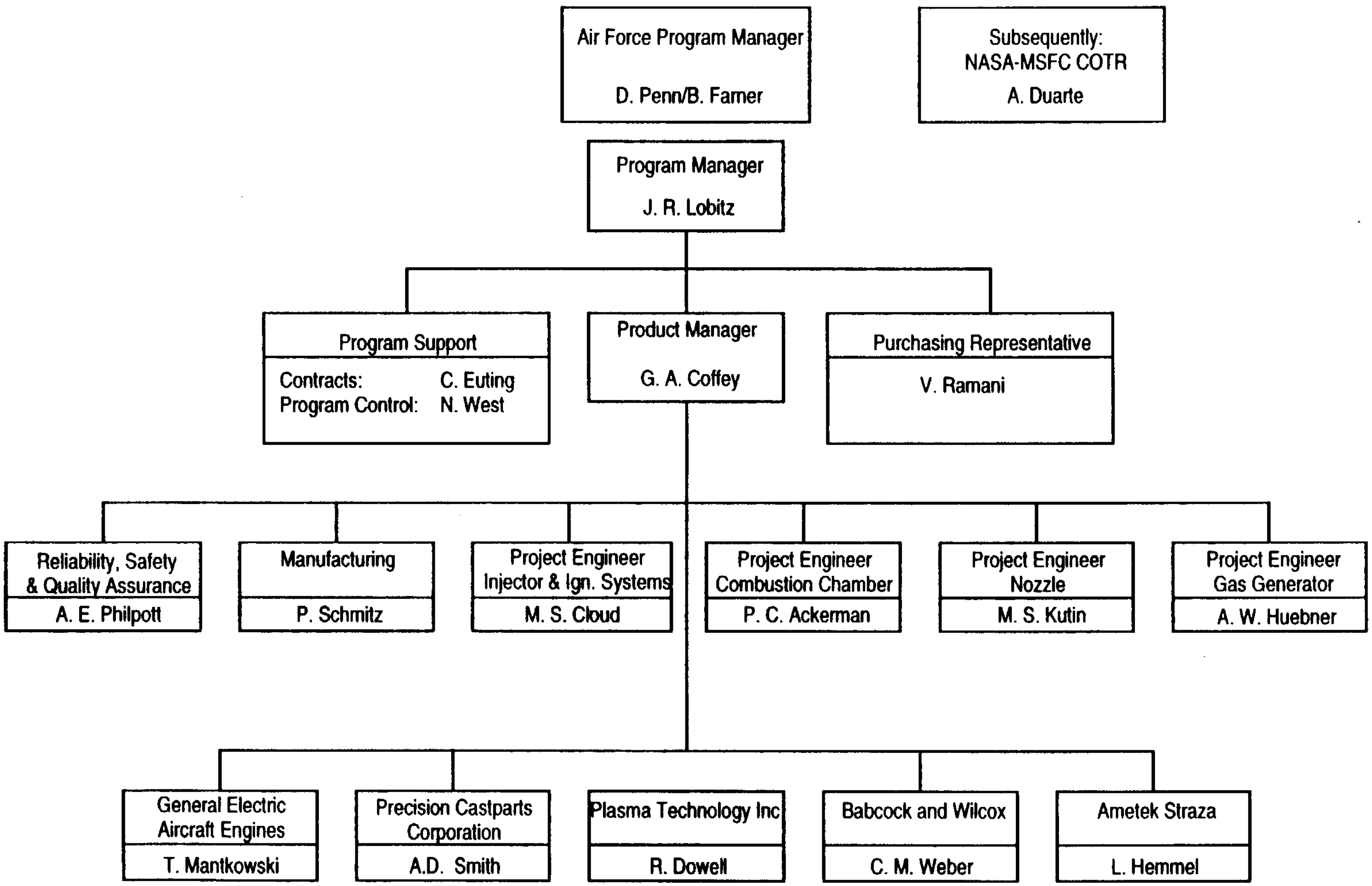
1.1 PROGRAM APPROACH

The program approach to component development utilized simultaneous engineering. Each component had a "product team", consisting of co-located specialists including Cost Analysis, Reliability, Manufacturing and Quality Assurance in addition to the required engineering disciplines. Key suppliers also participated in the development teams. This helped to ensure their participation in component development from the beginning of concept definition.

Each Baseline-1 design concept proposed for the thrust chamber and gas generator assemblies were traded with other concepts of merit. Trade studies were based on how well each concept addressed customer requirements, with emphasis on reliability and cost. Total Quality Management (TQM) techniques were also applied where appropriate to aid in assessing concept merits. Additional fabrication studies were performed as well to further distinguish from the most promising concepts. Hardware was then designed and fabricated to test certain trades. During this phase of the program, a cost and schedule performance control system (CSPC) was utilized to monitor program performance.

Upon program re-direction, the scope was limited to combustion chamber development with the focus on the Cast Jacket/VPS liner design. Materials and process development samples and mockups were emphasized to assess the concepts' ability to meet program goals.

ALS COMBUSTION DEVICES PROGRAM ORGANIZATION



ALS COMBUSTION DEVICES PROGRAM APPROACH

- **Baseline 1 design concepts were selected**
  - Results of analyses, studies, and testing to date
  - Judged to be lowest cost
  - Have good probability of meeting reliability and producibility goals
- **Alternate component concepts and fabrication methods were identified**
- **The baseline 1, alternate, and other concepts of merit will be traded**
  - Reliability
  - Maintainability
  - Engine cost
  - Vehicle cost
  - Material/processing maturity
  - Versatility to emerging requirements

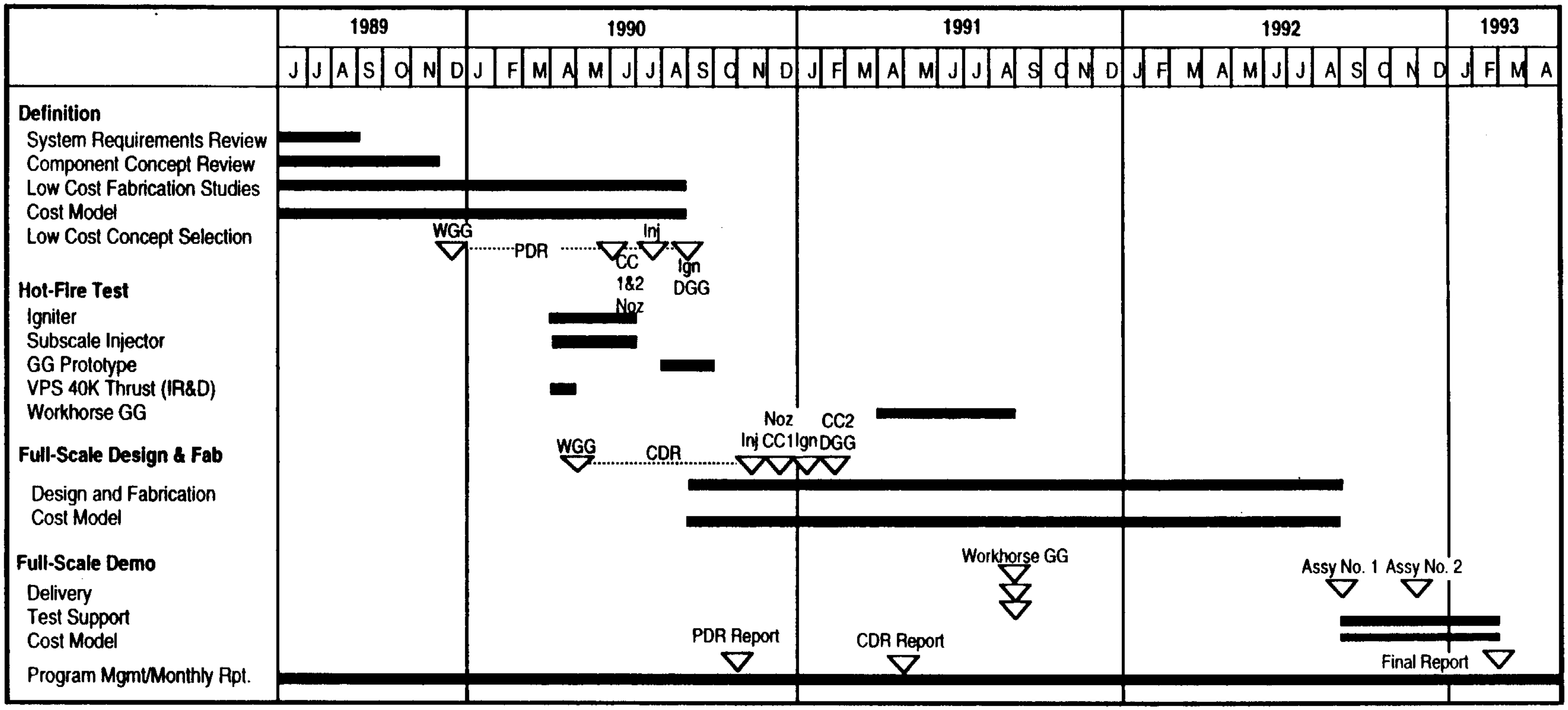
ALS COMBUSTION DEVICES PROGRAM APPROACH (Cont'd)

- **Concept validations will be performed**
  - Additional analyses
  - Laboratory hot-fire tests
  - Subscale hot-fire tests
  - Fabrication studies
- **Results of the trade studies and validations, and a Baseline 2 concept recommendation will be presented at PDR**
- **The Baseline 2 concepts will be designed and fabricated**
- **Simultaneously engineering will be used to accomplish low cost, high reliability designs**
- **The hardware will be delivered and demonstration tested at the Astronautics Laboratory test facility**

ALS COMBUSTION DEVICES PROGRAM APPROACH (Cont'd)

- Two complete demonstrator TCA and GGA assemblies will be delivered and tested
- Three workhorse gas generator assemblies will be delivered
- On site test facility support, including engineering, logistics, and spares, will be provided
- A credible combustion devices component cost model will be prepared and anchored with actual costs determined during the fabrication process
- A high level of customer participation is planned to ensure emerging ALS engine requirements and low cost goals are fully integrated

ALS COMBUSTION DEVICES PROGRAM SCHEDULE



LEGEND

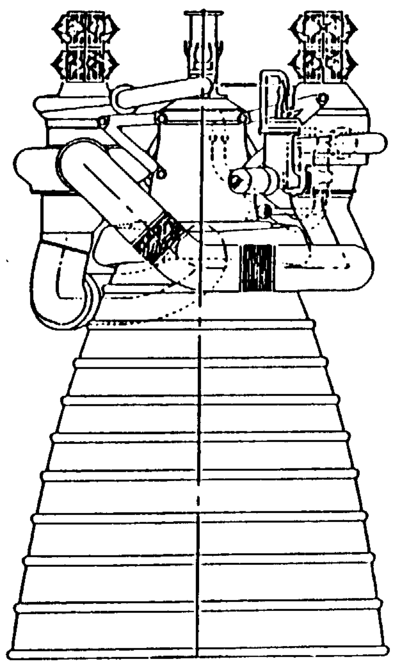
PDR - Preliminary Design Review
CDR - Critical Design Review
WGG - Workhorse Gas Generator
DGG - Demonstration Gas Generator
Inj - Injector
Ign - Igniter
CC - Combustion Chamber
Noz - Nozzle

1.2 DESIGN REQUIREMENTS

The geometric and operating design requirements were derived from the Space Transportation Main Engine (STME) definition. The requirements were updated as more detailed component analysis were completed throughout the program.

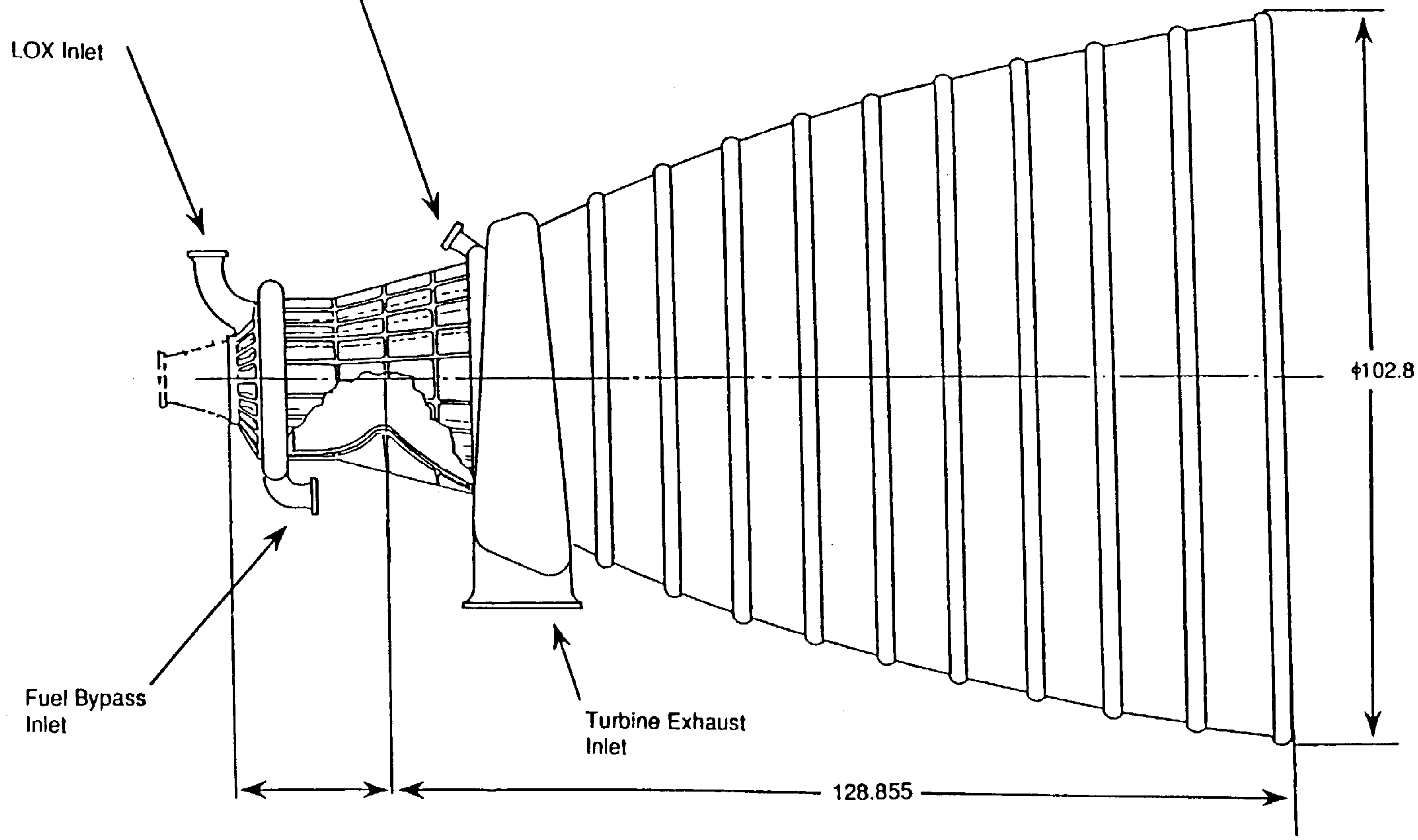
Requirements for the design included meeting increased structural margins over previous engines, as well as the ability to operate at higher thrust for development margin. Designs were also required to meet fracture mechanics analysis limits in critical areas to enhance reliability. Specific cost and reliability goals were established for each major thrust chamber component. Each design could then be objectively analyzed for its ability to meet design goals.

SPACE TRANSPORTATION MAIN ENGINE (STME)
ENGINE DESCRIPTION



• Cycle	Gas Generator
• Thrust, lb (vac)	580,000
(sl)	461,000
• Specific impulse, sec (vac)	435
(sl)	345
• Chamber pressure, psia	2250
• Engine mixture ratio, o/f	6.0
• Area ratio,	62
• Mission life	15
• Length, in	175
• Diameter, in	103
• Weight, lb	7073
• Gimbal capability, deg	±6

THRUST CHAMBER ASSEMBLY DESIGN APPROACH



ENGINE THRUST CHAMBER ASSEMBLY GEOMETRY

Parameter	STME
Injector diam. (in.)	21.78
Chamber throat diam. (in.)	12.91
Chamber length to throat (in.)	14.62
Contraction ratio	2.84
Combustion chamber expansion ratio	7.0
Combustion chamber exit diam. (in.)	34.17
Nozzle expansion ratio	62
Nozzle exit diam. (in.)	102.8

ENGINE THRUST CHAMBER ASSEMBLY OPERATING CONDITIONS

Parameter	STME
	Max
Thrust chamber thrust (lb)	580K (vac)
ηC^* (%)	99
P_c (psia)	2250
MR (O/F)	6.79
LOX flow rate (lb/sec)	1120
Fuel flow rate (lb/sec)	165
Coolant flow rate [MCC/noz (lb/sec)]	34/48
Fuel injection temperature (°R)	183
Injection pressure [O/F (psia)]	2587/2470
Combustion chamber heat input (btu/sec)	59.3K
Combustion chamber coolant ΔT (°R)	447

ENGINE LIFE REQUIREMENTS

- **Three ground acceptance tests**
  - 2 second ignition test
  - 250 second hot-fire test
  - 600 second hot-fire test
- **15 flight missions x 600 seconds each**
- **No hot-fire between flights**
- **Total operating life - 18 starts/9852 seconds**

DESIGN GROUNDRULES

- **Structural**
  - Design for operation at 105%
  - Utilize limit load factor of 1.2
    - For design/analysis process
    - Provides margin (robustness) for development
    - Provides margin for 2σ plus flight above 105%
- **Performance**
  - Optimize for nominal 100% operation (580K)
  - Minimum degradation at 105%

ALS STRUCTURAL CRITERIA

- **Limit Load Factor** — 1.2 (on nominal loads)
- **Primary Stress Safety Factors**
  - Yield — 1.1
  - Ultimate — 1.5
- **Life Safety Factors**
  - Low Cycle Fatigue — 4.0 (cycles)
  - High Cycle Fatigue — 1.25 (endurance)
  - Fatigue Crack Growth
    - Low Cycle — 4.0 (cycles)
    - High Cycle ($\Delta K_{th}/\Delta K_{dyn}$) — 1.0 (threshold)

COMPONENT COST AND RELIABILITY REQUIREMENTS

Component	Cost (1987 $)	Reliability*
Injector & Ignition System	$350K	0.99997 Injector 0.999998 Igniter Module (Injector & G.G.)
Combustion Chamber	$400K	0.99992
Nozzle	$400K	0.99986
Gas Generator	---	0.99993

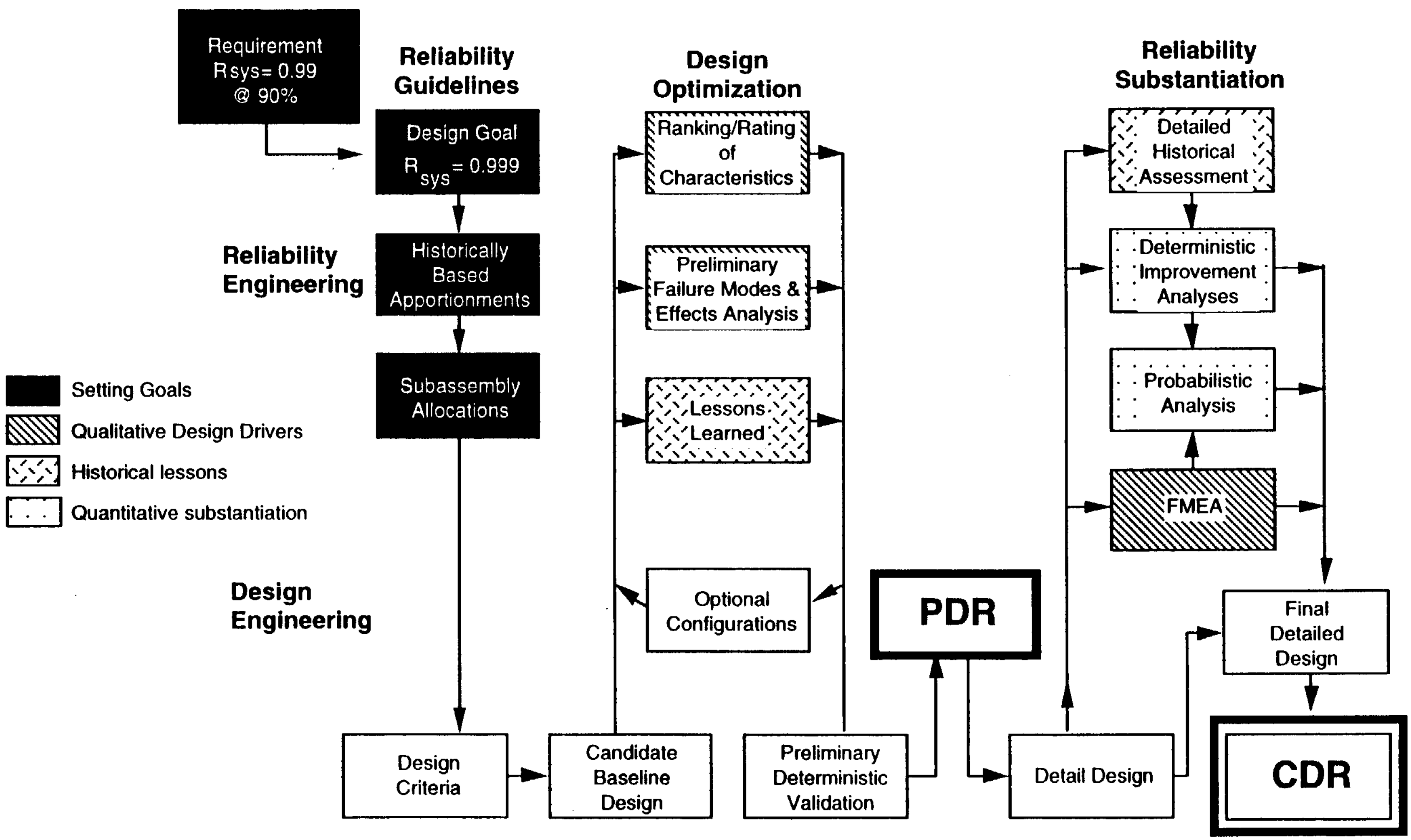
*As determined by probabilistic design analysis

2.1.1 Reliability Methodology

2.1.1 RELIABILITY METHODOLOGY

A two-fold analytical approach was used to evaluate component reliability. The primary approach was the use of Failure Modes & Effects Analysis (FMEA), which has been used on previous engine programs. This technique was used on both concept designs as well as critical processes used in the designs. Historical data bases from previous engine programs were used to aid in initial component reliability allocations. Critical design features identified by FMEA and structural analysis also underwent fracture mechanics and probabilistic design analysis. The extra analysis was used to quantify and refine the design to meet its reliability allocation.

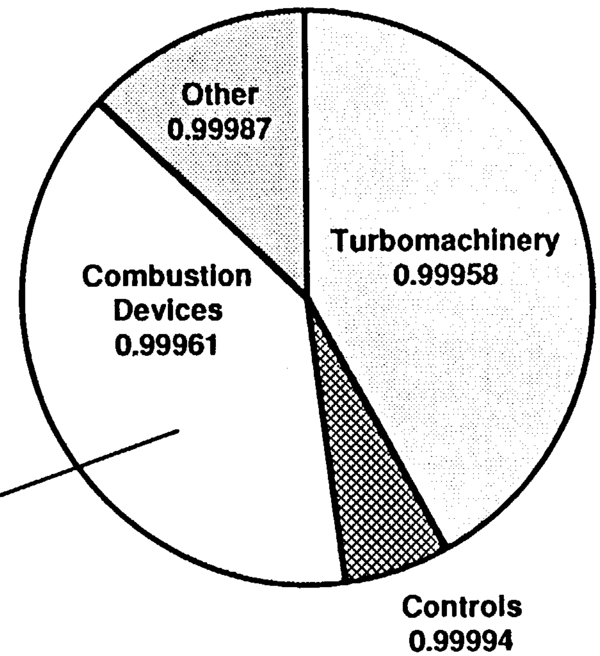
CONCURRENT ENGINEERING RELIABILITY DESIGN DEVELOPMENT



RELIABILITY DESIGN GOALS

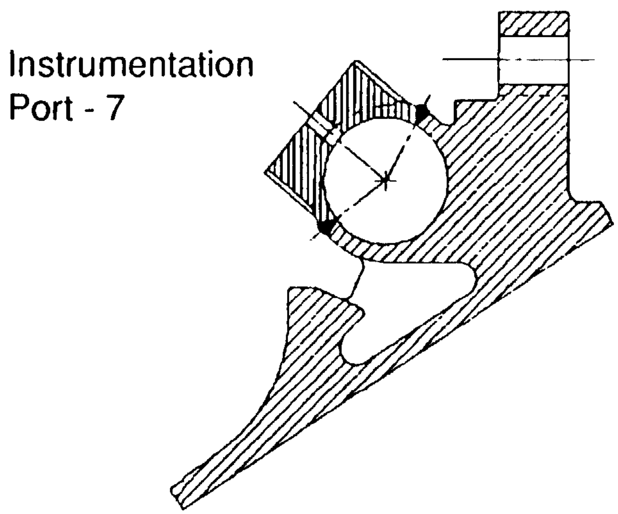
STEP
Requirement
0.99 at 90% Confidence

Rocketdyne
Reliability
Design Goal
$R_{sys} = 0.999$

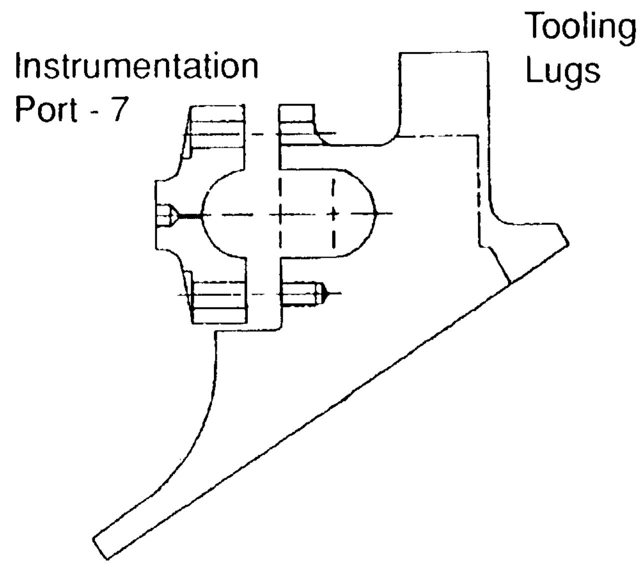


ADP Combustion Devices Components	Design to Allocation
Injector	0.99997
Nozzle	0.99986
Gas Generator	0.99993
Combustion Chamber	0.99992

RELIABILITY SCREENING EXAMPLE
AFT MANIFOLD CONCEPTS



2 Piece Casting, Welded Manifold Shell
(Concept 2)



2 Piece Casting, Bolted Manifold Shell
(Concept 5)

AC950913-207

RELIABILITY SCREENING RESULTS

Criteria	Weight Factor	MCC Concept No. 2 2 Pc. Casting Welded Shell	Rating	Rating x W.F.	MCC Concept No. 5 2 Pc. Bolted Manifold	Rating	Rating x W.F.
Ranking of Characteristics							
No. of part types	1 (3.1%)	4	10	10	6	15	15
Maintenance	1 (3.1%)	Leak check only	10	10	Leak & 120 bolt torque	30	30
Producibility	1 (3.1%)	Simple	10	10	Complex steps	15	15
Inspectability	2 (6.3%)	Welds only	10	20	122 bolts, 2 O-rings	15	30
Total no. of parts	4 (12.5%)	16	10	40	136	40	160
Preliminary FMEA	8 (25.0%)	2 Circumf. Welds	10	80	126 Fail Points	40	320
Historical Lessons Learned	15 (46.9%)	Welded Shell	10	150	High press., high vib., cryogenic joint	30	450
Total Rating				**320**			**1020**
		Relative Failure Rate		**1**	**Relative Failure Rate**		**3.2**
		$R_{MCC_{BL}}$ =		**0.99992**	$R_{MCC\#5}$ =		**0.99974**

ROLE OF THE PROCESS FMEA
Example: VPS Chamber

Product FMEA
- Coolant leak
- Channel blockage
- Inadequate heat transfer

Product C.I.L.
- Liner wall thickness
- Liner structural properties
- Incoming pressure

Process FMEA
- VPS process
- VPS material control

Process C.I.L.
- Power setting
- Gas flowrate
- Substrate temp
- Gun distance

Design of Experiment *
- Determines process insensitive to gas flowrate
- Sensitive to substrate temp
- Sensitive to gun distance

Process Optimization
- Optimum substrate temp is 1300 deg F.
- Hotter temps result in porosity
- Cooler temps give stick bonds

Process Control
- In process monitoring of strata temp, active temp control of strata temp
- Auto lock will not allow gun operation if strata temp is outside of parameters

* Last 3 steps in work and give hypothetical examples for illustrative purposes

PROCESS FAILURE MODE AND EFFECTS ANALYSIS

Vacuum Plasma Spraying

Date: 7-30-90
Prep. By: Lillian Ng / K. Reinhardt
Page:

Process Function	Failure Mode	Potential Effect(s) Of Failure	Potential Cause(s) Of Failure	Current Control(s)	Recommended Action(s)	Assigned To/ECD	Action(s) Taken/ Implement Date.	Impact On Design
VPS Deposit strata which meets structural, thermal, and adherence requirements	Out of dimensional tolerance	(Rework)	Vacuum too low Vacuum too high	Computer control				
	Insufficient bond strength	(Rework/scrap)	Run out of powder	Monitor powder, gas pressure				
	Poor structural properties	(Rework/scrap)	Powder feed clogs up					
	Poor thermal properties	(Rework/scrap)	Power outage Parameter error including: gun distance, power setting, substrate temp, primary gas flowrate, work velocity.	Computer control				
			Operator error	Planning				
Cool down	Cool too fast	Produce residual stress	Operator error	Computer control				
	Cool too slow	Grain growth degrades properties						

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PRODUCT AND PROCESS FMEA'S STATUS

	In Work	Complete
Product		
• Nozzle		
• Brazed Tube		X
• Convoluted Nozzle		X
• Injector		X
• Combustion Chamber		
• LIDB		X
• VPS		X
• Gas Generator		
• Coaxial		X
• Fan		X
Process		
• Vacuum Plasma Spray		X
• LIDB		X
• Plating		X
• Laser Welding	X	
• Welds Of Castings	X	
• Explosive Forming	X	
• Investment Casting	X	

FRACTURE MECHANICS ANALYSIS STRATEGY FOR ENHANCED RELIABILITY

- **Produces a more robust, defect-tolerant design**
- Allows process-intrinsic flaws with less rework/scrap
- **F/M analysis based on "90/95" NDE flaw size**
  - Dye penetrant for surface flaws
    - 0.100" long x .020" deep
  - Ultrasonic for EB weld root flaws
    - 3x area of reflector standard
- **Fatigue crack growth criteria**
  - Low cycle $K_I \leq K_{Ic}$ @ 4 x design life
  - High cycle $\Delta K_{dyn} \leq \Delta K_{th}$

PROBABILISTIC ANALYSIS USED IN THE DESIGN PROCESS

- **Approach**
  - Select critical locations and identify known failure modes (FMEA)
  - Perform deterministic analysis
    - Compare calculated safety factors to structural criteria
  - Perform probabilistic analysis
    - Compare calculated reliabilities to component allocation
- **Assumptions and Limitations**
  - All random variables have normal distribution
  - Random variables are uncorrelated
  - Standard deviations estimated
  - Burst and HCF crack initiation failure modes
  - Fracture mechanics requires flaw statistics

2.1.2 Cost Model Methodology

2.1.2 COST MODEL METHODOLOGY

A major objective of this program was the development of a cost model for accurately projecting the costs of the operational combustion devices hardware. A Combustion Devices Cost Model (CDCM) was created in a spreadsheet program (Microsoft Excel) and used throughout component design.

The model consists of two tiers. The first tier is used for concept selections and trade studies. It is only based on size and complexity relationships and therefor easy to use. The second tier is much more detailed and requires more inputs. It is useful for evaluating manufacturing process methods and detail design trades as well as projecting the final designs' cost.

Each tier is also separated into three modules. The touch labor module takes standard hours specified at the fabrication process level and applies appropriate cost factors and labor rates. The second module calculates support labor hours based on the RS-27 engine program and applies appropriate labor rates. The last module calculates material costs based on price quotes from vendors and procurement factors.

COST MODEL OBJECTIVES

- **Project production cost of combustion device components allowing for variations in engine design parameters**
  - Thrust : 500 klb - 700 klbf
  - Chamber Pressure : 1900 psia - 2250 psia
  - Area Ratio : 20:1 - 70:1
  - Mixture Ratio : 5.2:1 - 6.0:1

- **Use for trade studies, concept selections, and evaluation of low cost manufacturing methods**

MODELING APPROACH

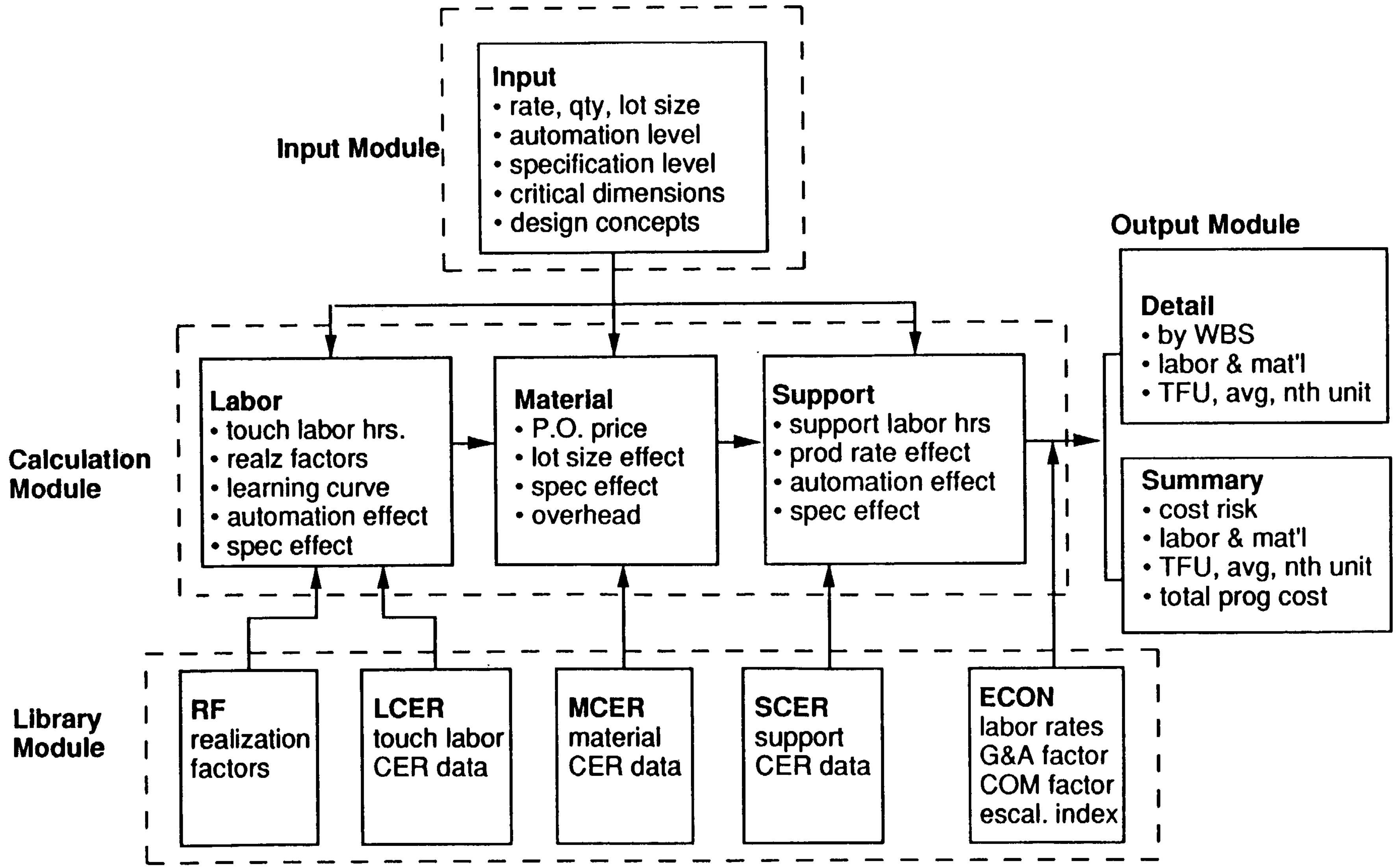
- **Two tier, process oriented model to estimate cost at two levels of precision**
  - Evaluate costs of various design approach at cursory level for concept trades
  - Flexibility for incorporating alternate design concepts (Rocketdyne and others)
  - Allow variations in programmatics (e.g. rate & quantity)
  - In-depth, accurate costing at process level for detail design trades
- **Anchor model with actual prototype fabrication cost data**

MODELING APPROACH

- **Tier 1 - Design Approach Model**
  - Useful for design/configuration tradeoffs
  - Size and complexity driven cost estimating relationships (CERs)
  - CERs based on process strings
  - Easy to use
  - Coded on spreadsheet program (Microsoft Excel)

- **Tier 2 - Detail Design Model**
  - Useful for detail process tradeoffs
  - Bottoms-up costing method
  - Requires more inputs
  - Suitable for designer/manufacturing engineer users

COST MODEL ARCHITECTURE



COST MODEL FORMULATION - TOUCH LABOR MODULE

- **Establish manufacturing process planning**
- **Estimate std. hours for baseline & alternate designs**
- **Formulate std. hours as functions of size & complexity**
- **Quantify the following cost factors:**
  - Realization factor (at the process level)
  - Automation factor (at the process level)
  - Specification factor (at the process level)
  - Quantity factor (Crawford learning curve)
- **Multiply the std hours with cost factors**
- **Apply the appropriate labor rate**

COST MODEL FORMULATION - SUPPORT LABOR MODULE

- **Four major support categories (from Contract & Pricing):**
  - Support to fab and assembly
  - Level of effort
  - Fixed expenses
  - Material support
- **Determine support labor hours (based on RS-27 Prog.)**
- **Determine the effects of higher production rates**
- **Quantify the effect of "low cost" manufacturing concepts**
- **Apply the appropriate labor rate**

COST MODEL FORMULATION - MATERIAL MODULE

- Obtain price quotes from suppliers
- Formulate material costs as functions of size
- Quantify the effect of procurement lot size variations
- Determine material procurement overhead and taxes

AUTOMATION EFFECT

- **Reduced touch labor hours**
  - Fewer machine operators due to integrated automation (lower automation factor)
  - Reduced reworks and delays due to robust designs, automation, and more effective scheduling and shop floor control (lower realization factor)
- **Reduced support labor hours**
  - Fewer support personnel due to integrated automation, TQM concept, and simplified hardware design
  - Economy of scale at higher production rates
- **Higher labor rates for CIM plant**
  - Highly skilled, technically oriented workers
  - Higher overhead due to large capital investments (i.e. depreciation of plant and equipment)

COST MODEL EXAMPLE
COMBUSTION CHAMBER INPUT

Engine Design Parameters	
Thrust (klb)	580
Chamber pressure (psia)	2250
Mixture ratio	5.8:1
Area ratio	40:1
Programmatic Variables	
Total production quantity	500
Prior quantity	0
Net production quantity	500
Production rate (units/year)	50
Procurement lot size (units/year)	50
Year-Dollar to report	1990
Specification level (1,2, or 3)	1
Automation level (1,2, or 3)	2
Nth unit cost to report	500
Critical Dimensions	
Forward diameter (in.)	21.00
Aft diameter (in.)	34.80
Throat diameter (in.)	13.20
Chamber length (in.)	35.60
Number of coolant channels	540.00
Surface area (sq. in.)	2562.28
Design And Fabrication Approaches	
Aft manifold type	2
1. One-piece casting	
2. Two-piece assembly	
Closeout/Jacket Type	3
1. Ni-Co closeout and jacket	
2. ED Ni-Co closeout, cast jacket	
3. VPS closeout and jacket	
Liner Type	2
1. Wrought	
2. Powder Metal	

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COST MODEL EXAMPLE
COMBUSTION CHAMBER OUTPUTS

WBS	Item Description	TFU Labor ($)	TFU Material ($)	TFU Total ($)	Average Unit Labor ($)	Average Unit Material ($)	Average Unit Total ($)
100	Final assembly	6,680	2,315	8,996	4,751	2,315	7,067
110	Chamber assembly - Grayloc	5,412	0	5,412	3,849	0	3,849
120	Grayloc fitting	0	492	492	0	492	492
130	Chamber assembly - plated structure	0	0	0	0	0	0
140	Chamber assembly - bolted structure	0	0	0	0	0	0
140	Chamber assembly - VPS	30,233	18,885	49,118	21,502	18,885	40,387
150	Chamber assembly - cold gas wall	0	0	0	0	0	0
160	Chamber assembly - slot closeout	0	0	0	0	0	0
170	Chamber assembly - LIDB	52,372	14,182	66,554	37,247	14,182	51,430
180	Liner - slotted	19,560	0	19,560	13,912	0	13,912
190	Liner	7,148	35,503	42,651	5,084	35,503	40,587
200	Aft manifold assembly - 1 pc.	0	0	0	0	0	0
210	Aft manifold assembly - 2 pc.	8,409	0	8,409	5,981	0	5,981
220	Manifold casting	611	43,996	46,607	434	43,996	44,430
230	Insert forging	3,013	6,947	9,959	2,143	6,947	9,089
240	Forward flange assembly	8,452	347	8,799	6,011	347	6,358
250	Forward flange forging	2,940	4,283	7,223	2,091	4,283	6,374
260	Closeout forging	623	1,737	2,360	443	1,737	2,180
270	Nozzle attachment	8,803	23,261	32,064	6,261	23,261	29,522
	Total Hardware	154,255	151,949	306,205	109,708	151,949	261,658
501	% of fab - Recurring tooling	20,889		20,889	14,856		14,856
502	% of fab - Engr & Test	30,189		30,189	21,471		21,471
503	% of fab - Q.A./inspection	30,189		30,189	21,471		21,471
504	LOE - Mfg & Facil	66,240		66,240	66,240		66,240
505	LOE - Engr & Test	11,393		11,393	11,393		11,393
506	LOE - QA	12,909		12,909	12,909		12,909
507	LOE - Mgm't & Repro	1,985		1,985	1,985		1,985
508	Fixed support expenses	557		557	557		557
509	Material control		106	106		106	106
510	Material administration		209	209		209	209
511	Receiving/source inspection		694	694		694	694
	Subtotal - support	174,351	1,008	175,359	150,882	1,008	151,890
	Subtotal - hardware & support	328,607	152,957	481,564	260,591	152,957	413,548
	G&A	34,504	16,061	50,564	27,362	16,061	43,423
	Total	363,110	169,018	532,128	287,953	169,018	456,971

touch labor rate ($/hr)	$XX.XX	production rate	50
support labor rate ($/hr)	$XX.XX	procurement lot size	50
G&A + COM + Fee (optional)		production quantity	500
automation level	2	year-dollar reported	1,990
specification level	1	Nth unit labor hours	2,286

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2.2 MAIN INJECTOR

To aid in the design of the main injector, past designs for LOX/hydrogen injectors were reviewed for cost and reliability drivers. The SSME and J-2 Injector designs utilized multiple forgings welded together for low weight and a high number of coaxial elements for performance, requiring hundreds of parts. Both of these features are costly and detract from reliability. Reliability concerns for these injectors also stemmed from combustion stability and LOX post fatigue which have caused engine failures in the past.

To address the cost and reliability drivers, a concept was developed which utilized high strength structural investment castings to reduce the number of parts and joints at the expense of added weight. The concept also integrated the face nut and fuel sleeve (similar to the J-2 design) used on the coaxial element to reduce the number of parts. The design would lend itself to cost improvement by incorporation of advanced manufacturing techniques to drill the high number of holes (thousands) in the injector and possibly to fabricate the LOX posts integral to the body.

Combustion stability would be obtained by varying the LOX post lengths and using baffles, as determined by detailed stability analysis. Provisions for acoustic cavities, if needed, are included in the design. Margin for LOX post fatigue would be obtained by injecting the fuel into the post array near the top of the posts. This minimizes post whirling so that flutes would not be needed on the outside of the posts as used in the SSME injector.

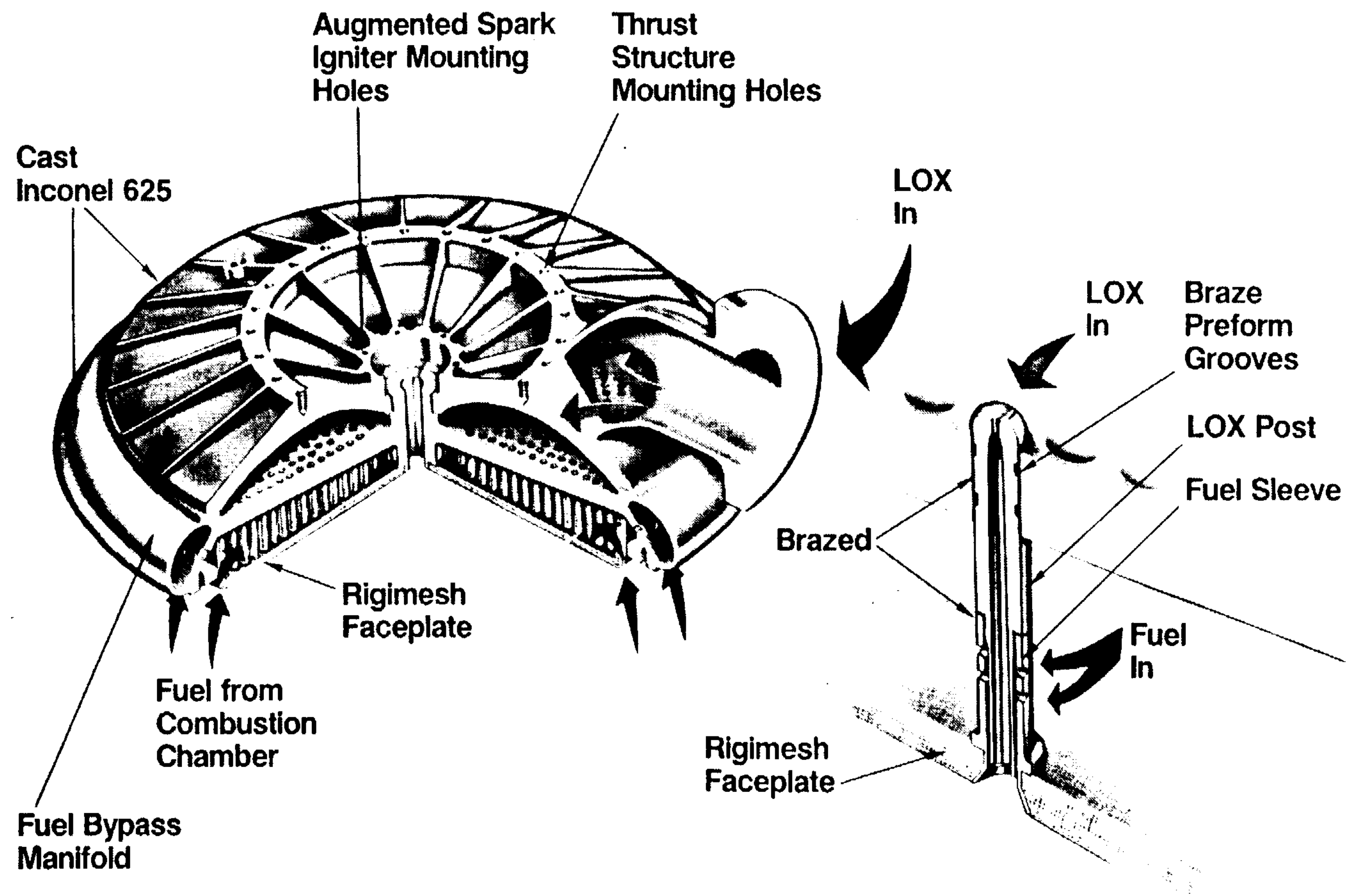
To address costs associated with the high number of elements used in past injectors, four subscale injectors were designed and fabricated with varying numbers of elements. Testing these injectors would give a performance versus element density curve that could be used to determine the fewest number of elements in the full scale injector that still obtains high performance while maintaining good combustion stability.

The charts that follow describe in detail the work associated with the main injector design effort as listed below:

- 2.2.1 Concept Selection
- 2.2.2 Design and Analysis
  - Design Configuration
  - Structural Casting Material Selection
  - Casting Design Details
  - Casting Structural Analysis Summary
  - Hydrogen Mixer Design and Analysis
  - Combustion Stability Analysis
  - Inspection Technologies Assessed
  - Manufacturing/Cost Analysis
- 2.2.3 Subscale Injectors
- 2.2.4 Main Injector Results

2.2.1 Concept Selection

BASELINE — 1 INJECTOR DESIGN



MAIN INJECTOR
COST AND RELIABILITY DRIVERS

- **Cost drivers**
  - Labor associated with machining and welding of forged parts
  - Fabrication and assembly of large number of elements on coax injector
- **Reliability drivers**
  - Combustion stability
  - LOX post fatigue

PROPOSED COST REDUCTION METHODS

- **Structural investment castings**
  - Requires few structural welds
  - Eliminates majority of machining forged parts would require
- **Reduced number of elements**
- **Automated laser drilling**
  - Interpropellant plate
  - Rigimesh faceplate
  - Element fuel sleeve inlet holes
- **Integrally cast posts**

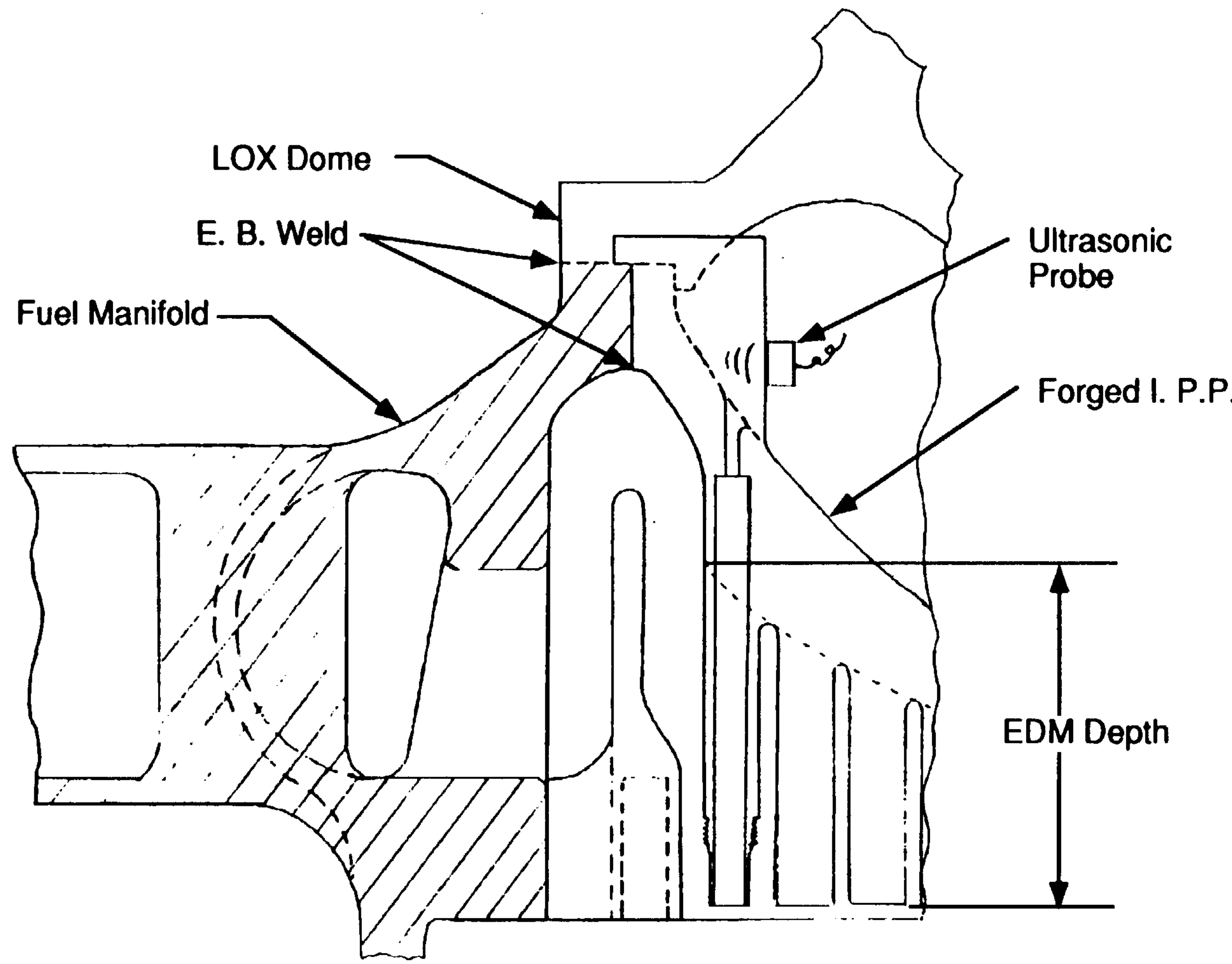
BASELINE MAIN INJECTOR DESIGN FEATURES

- 550 coaxial elements
- Brazed element construction
- Cast manifold construction
- Rigimesh faceplate
- Capability for adding acoustic cavity
- Single LOX dome inlet
- Single fuel feed manifold
- Bolt-on ignition system

INTEGRAL POST (EDM) INJECTOR CONCEPT

- **Advantages of electrical discharge machining**
  - Eliminates nickel plating and braze operations for posts
  - Reliability enhanced by eliminating interpropellant joints
  - Flush orifices gives better drainage
  - Fewer parts to track and store
- **Concerns**
  - Time to EDM
  - Capital intensive/high recurring tooling cost
  - Fuel flow concern for relatively short EDM depth
  - Recast layer difficult to remove
  - Expensive to repair post (drill, plate and braze new one)
  - Difficult to inspect
- **Lower element density helps EDM post viability**
  - Wide gap between posts for fuel flow allow shorter EDM depth

ELECTRICAL DISCHARGE MACHINED LOX POST/INTERPROPELLANT PLATE CONCEPT



INTEGRALLY CAST LOX POST INJECTOR

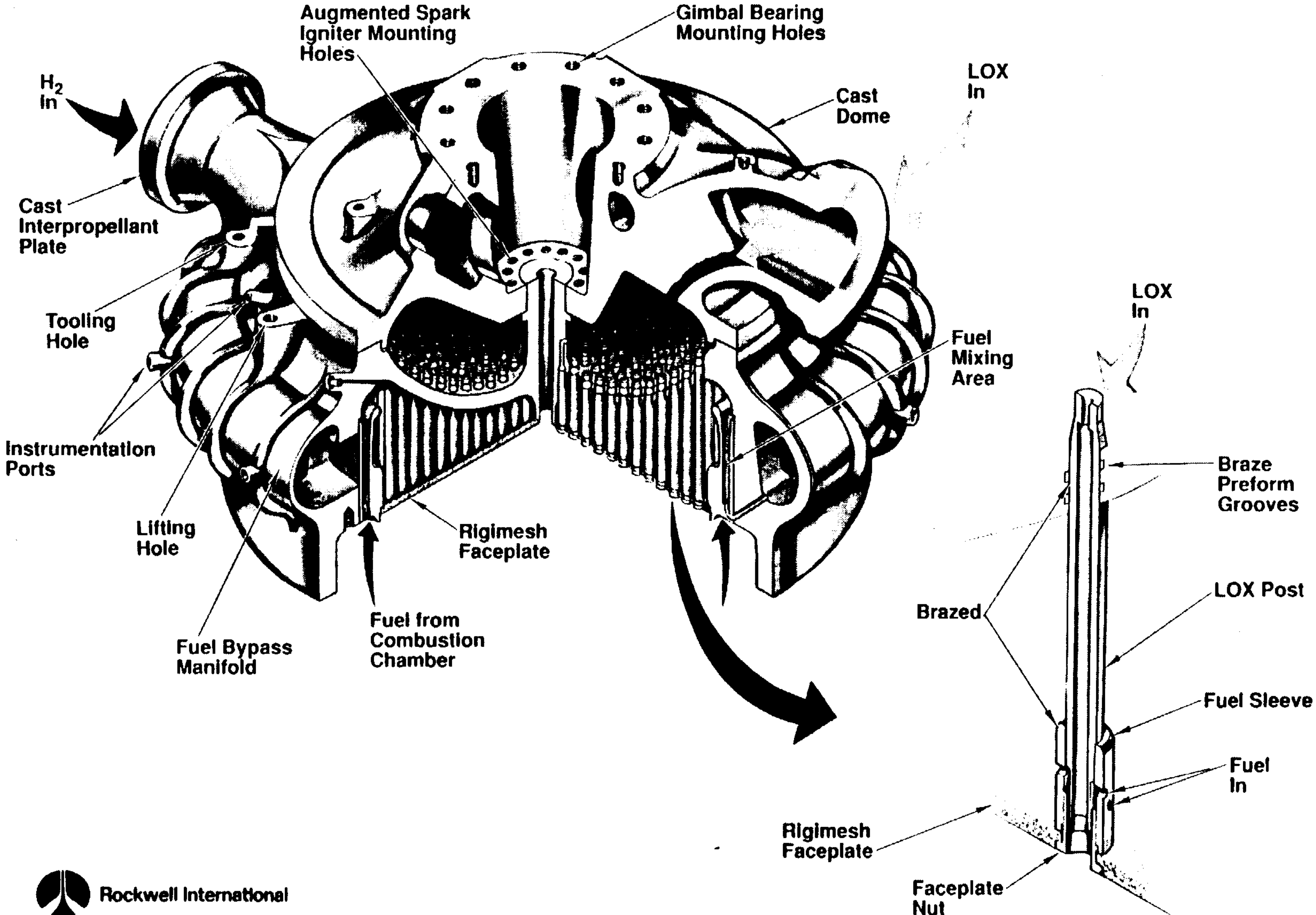
- **Same advantages as EDM'ed LOX post concept**
- **Concerns**
  - Capability limited to approximately 300 elements
    - Low performance
    - Chamber wall compatibility
  - Difficult to inspect and repair posts
  - Development would be high risk
  - Current cost estimate shows higher cost

BRAZED POST CONCEPT SELECTED (Baseline - 1 Design)

- **Advantages**
  - Demonstrated producibility and reliability on SSME preburners
  - Only two welds
  - Minimized machining
  - Lowest cost
- **Concerns**
  - Casting the interpropellant plate (IPP) and fuel manifold may require two pieces
  - Drainage with LOX posts not flush to IPP

2.2.2 Design, Analysis and Results

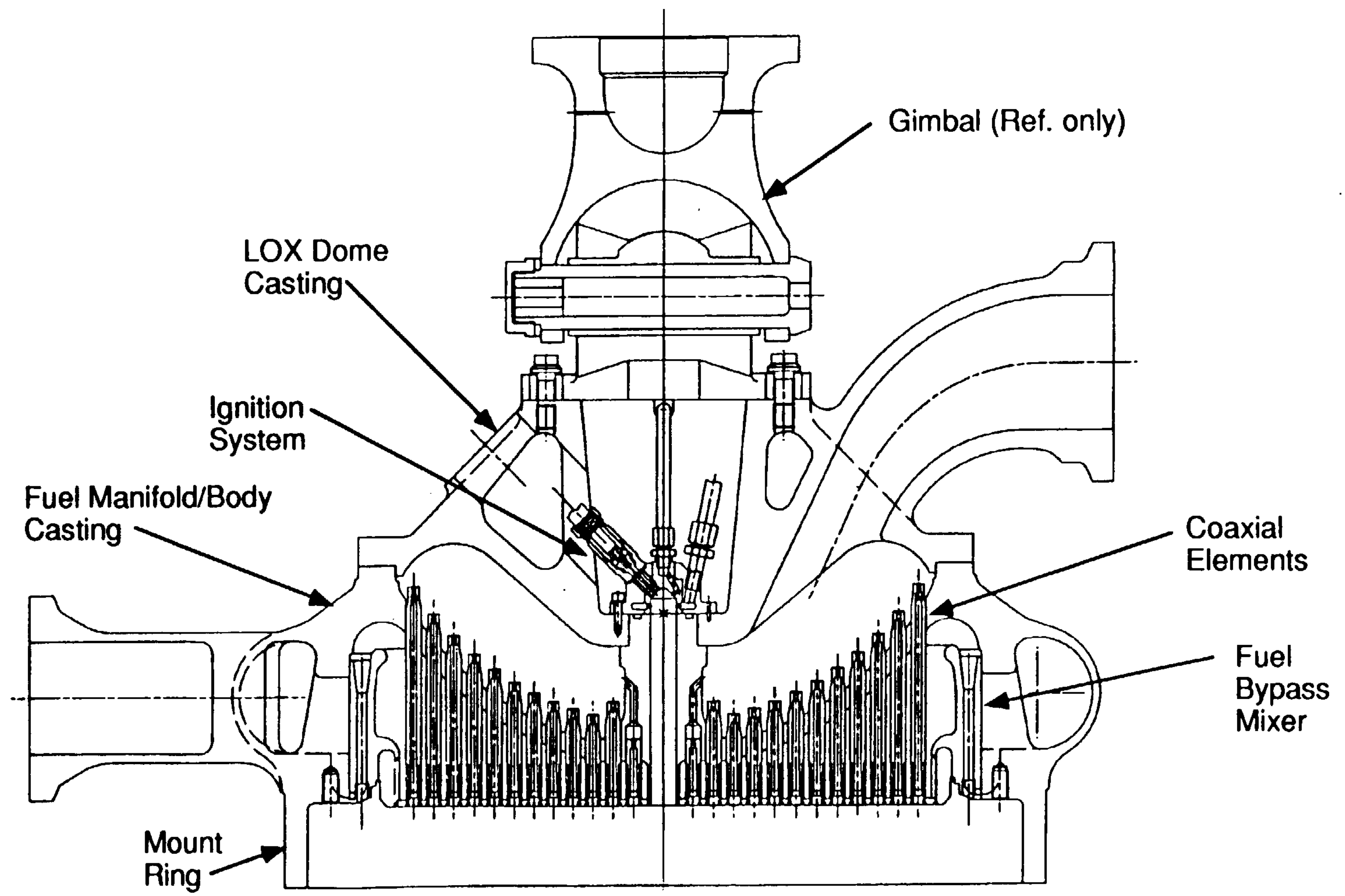
Injector Assembly



Rockwell International
Rocketdyne Division

LC91c-30-2

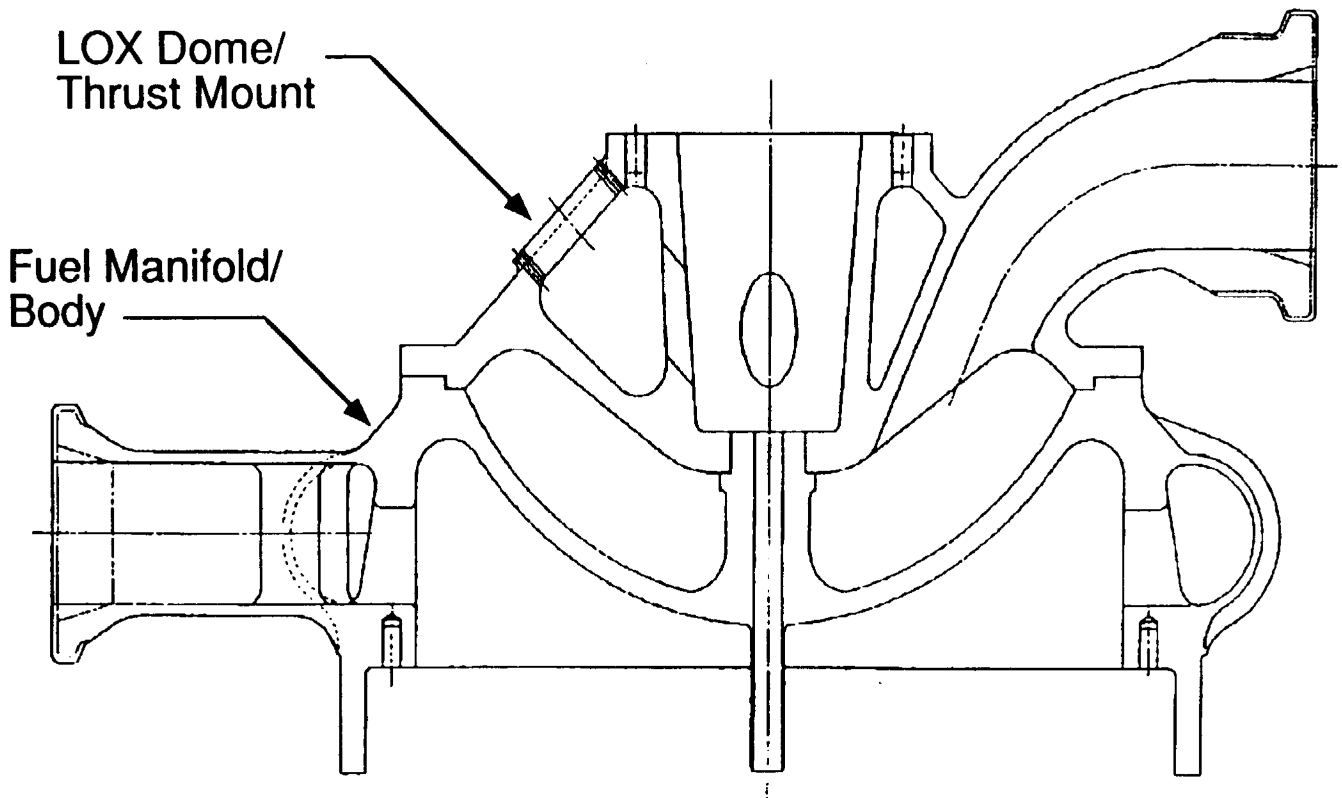
ALS INJECTOR ASSEMBLY
Final Layout



MAIN INJECTOR DESIGN EVOLUTION

- Fuel manifold core support/inspection windows on manifold I.D.
- LOX post length variation increased to avoid post-mode combustion instability
- Thrust mount made integral with LOX dome to relieve stress on LOX dome/fuel manifold weld
- Actuator/turbopump mount ring added to fuel manifold base
- Fuel bypass/combustion chamber coolant mixer added

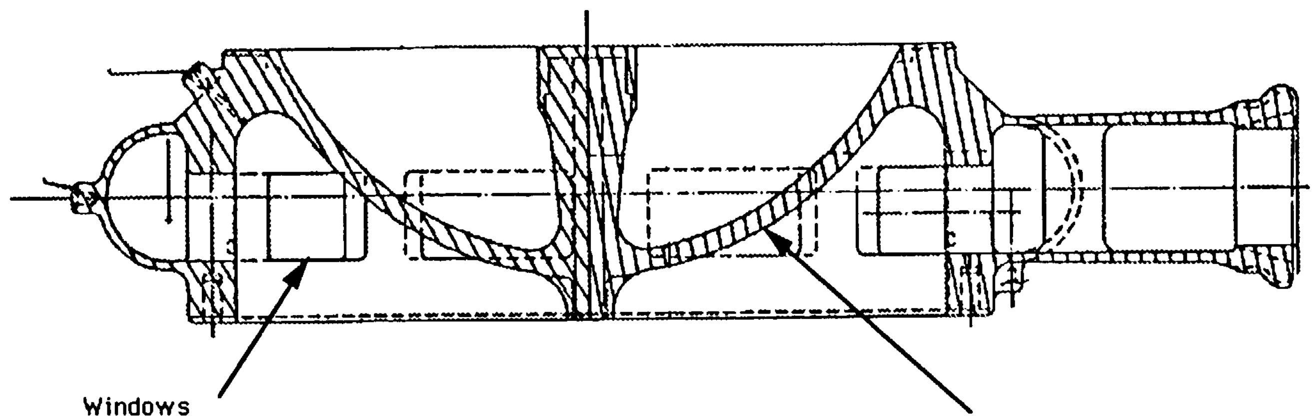
MAIN INJECTOR STRUCTURAL CASTINGS
Inconel 625



INCONEL 625 SELECTED FOR INJECTOR CASTINGS

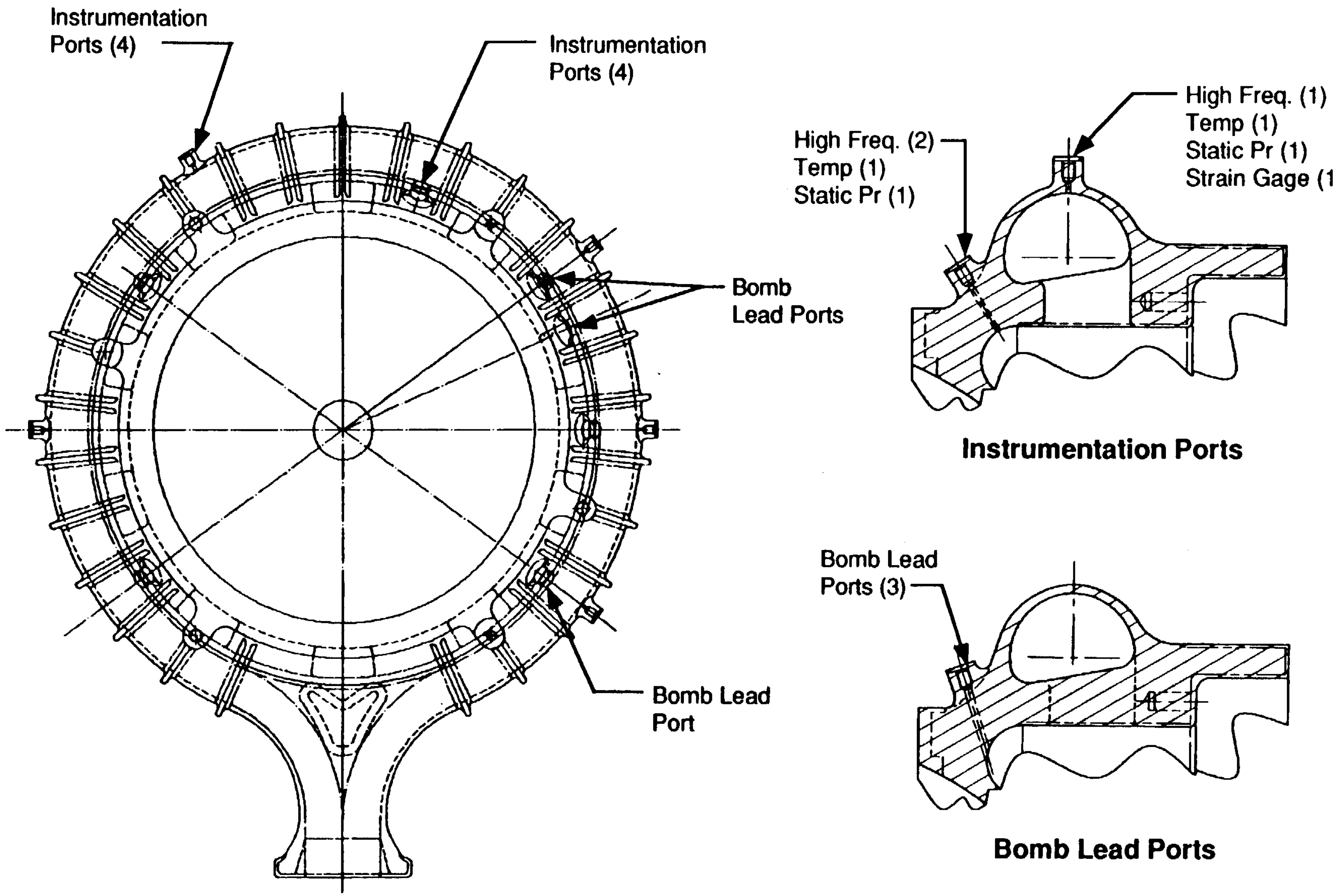
- **Proven usage record**
  - Brazing injector posts - 20 years of experience
  - Stability (solid solution strengthened)
  - Weldability
  - Castability
  - Corrosion resistance
- **Adequate hydrogen environment embrittlement (HEE) resistant**
  - No protective plating required
- **Standard 2050 F HIP cycle works well - (most INCONEL 625 investment castings are not HIP'ed)**
  - Programs with GE and PCC

FUEL MANIFOLD/BODY



- **Features**
  - Injector body cast integral with fuel manifold
  - No welds - manifold windows on I.D.
  - Inspectable
  - Repairable
  - Adequate mixing room
  - Large curvature of interpropellant plate increases variation of LOX post lengths

FUEL MANIFOLD/BODY
Instrumentation Ports



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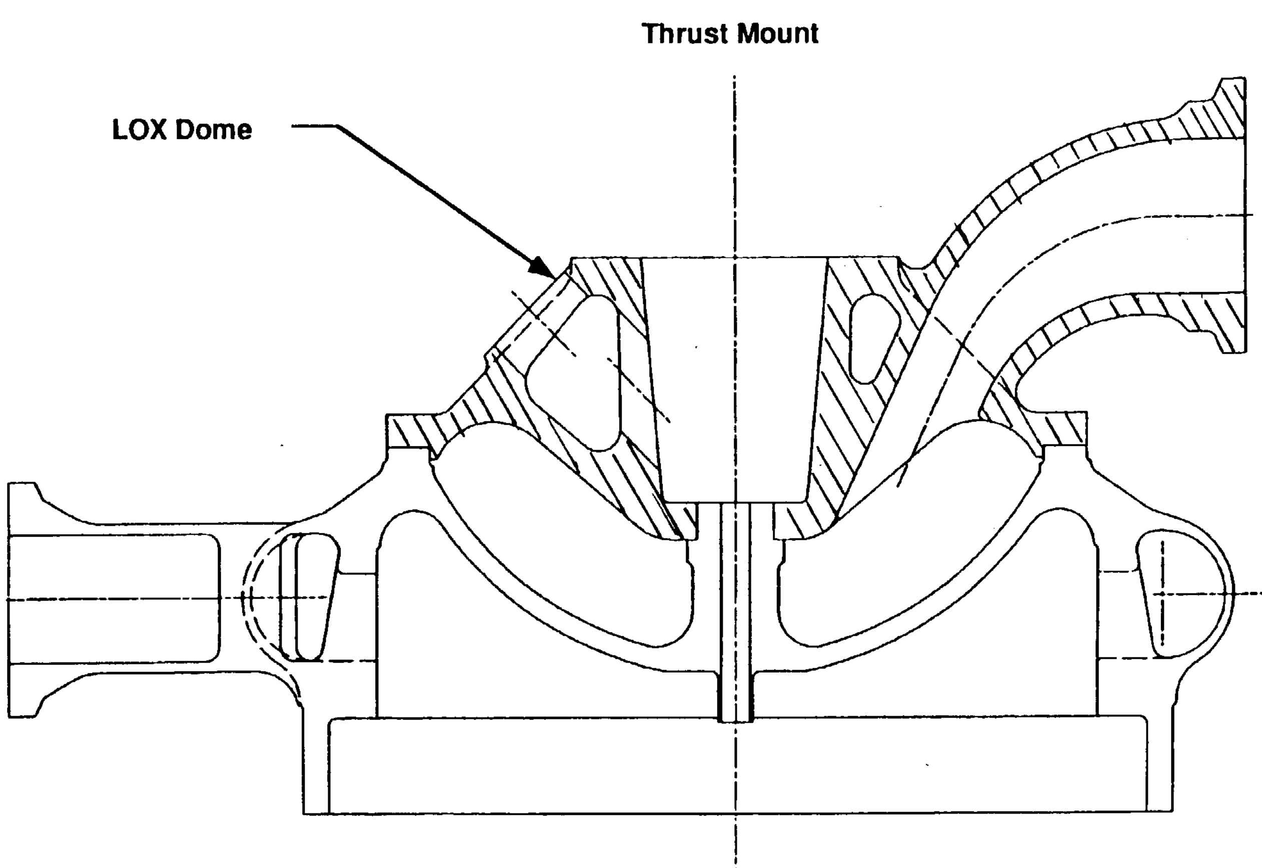
INJECTOR LOX DOME CASTING

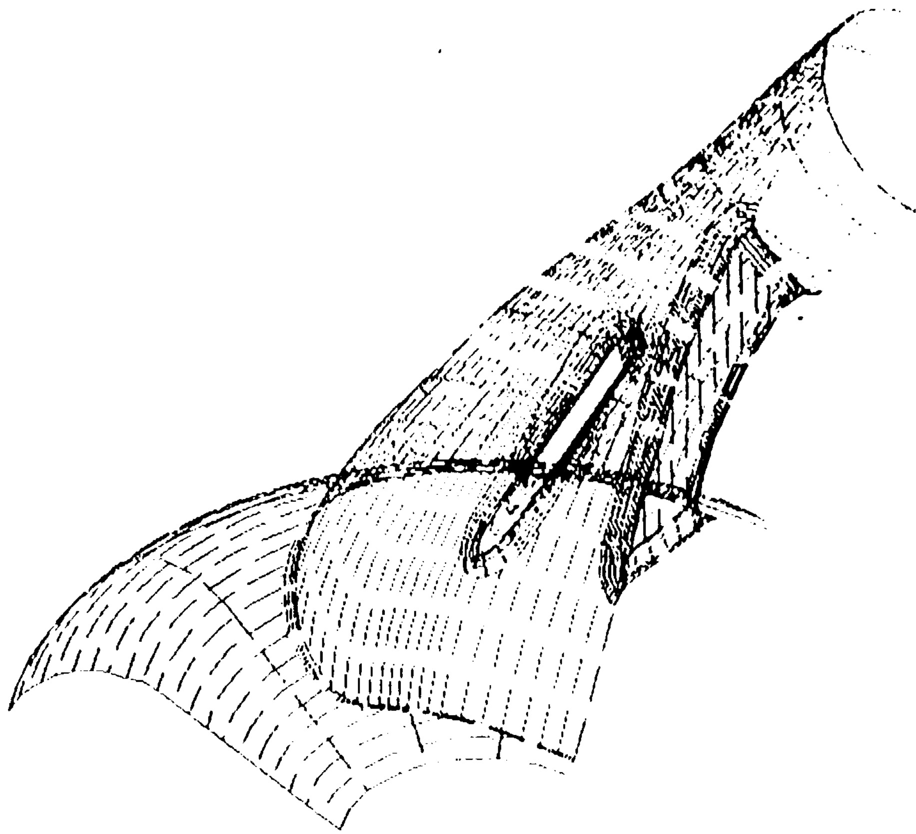


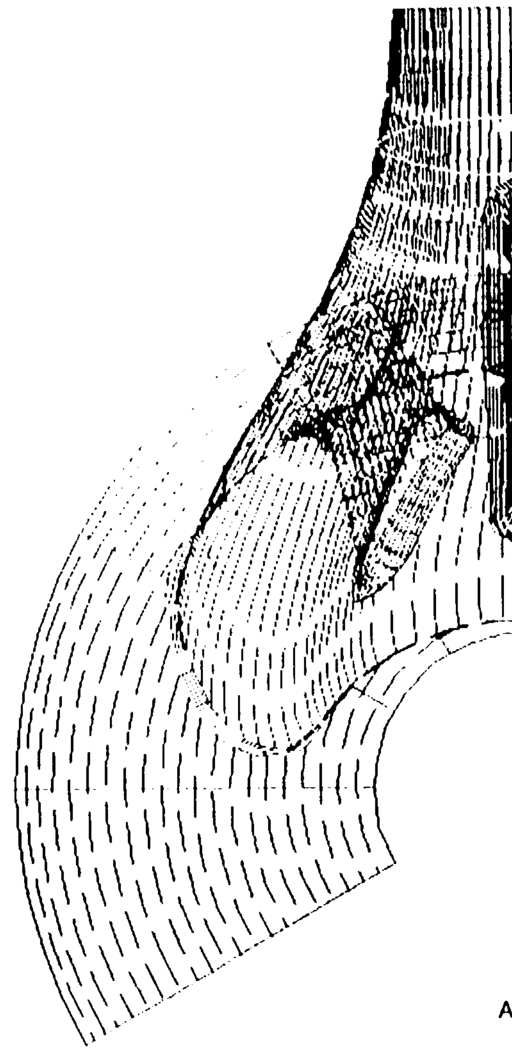
INJECTOR LOX DOME DESIGN STATUS

- **LOX dome design near completion**
  - 3-D CAD model completed
    - Model refined for computer aided manufacturing use
  - Dome axisymmetric structural analysis completed
  - LOX inlet 3-D structural analysis in work
  - Majority of casting drawing complete
    - LOX inlet views in work

LOX DOME INLET CAD MODEL

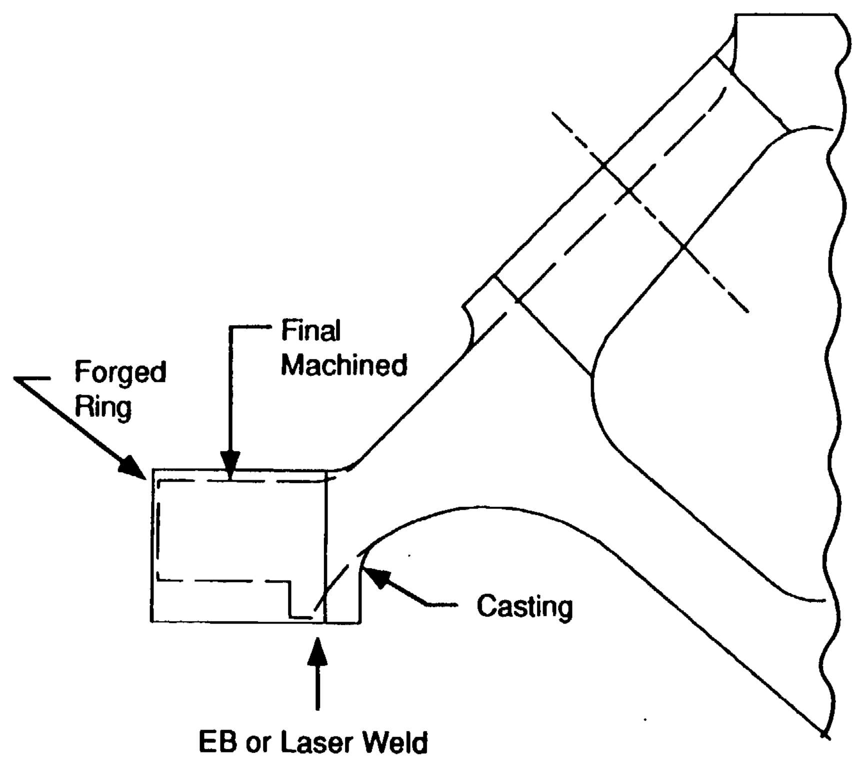
- To be supplied directly to casting vendor for tooling design



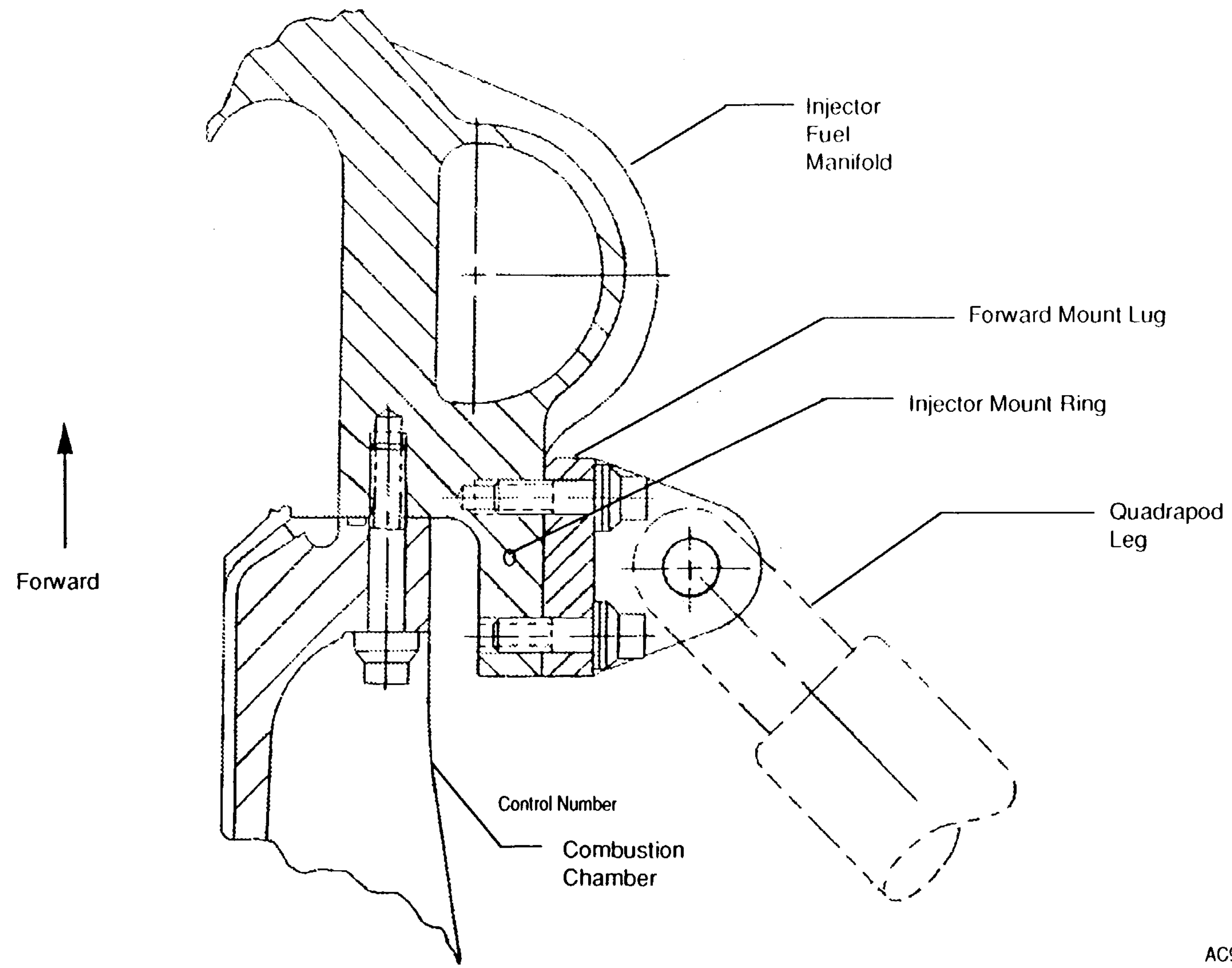


ALTERNATE LOX DOME WELD CONFIGURATION

- Fall-back configuration if casting ultrasonic inspection does not provide required defect resolution



INJECTOR MOUNT RING ATTACHMENT



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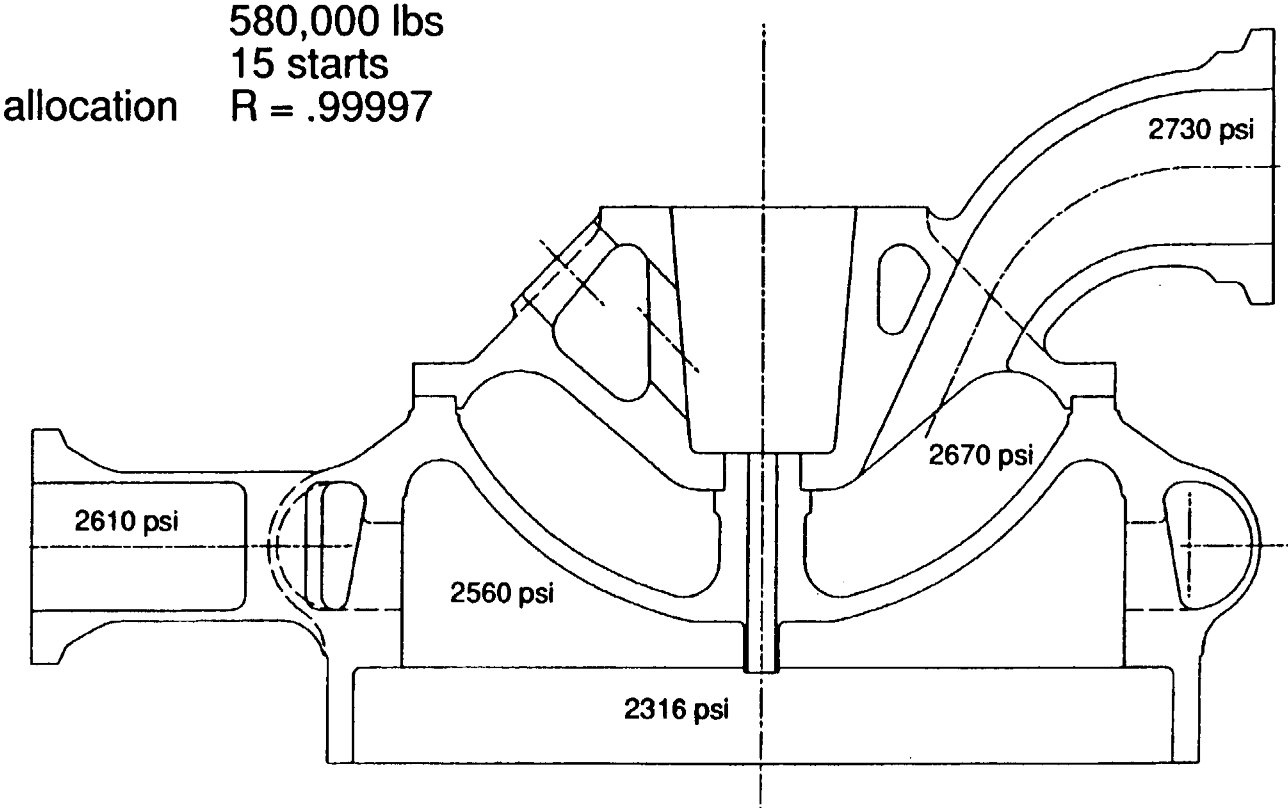
INJECTOR STRUCTURAL ANALYSIS INPUTS
(Nominal Values)

Thrust	580,000 lbs
Cycle life	15 starts
Reliability allocation	R = .99997



Note: Nominal pressures increased by 5% for analysis to account for "thrust growth"

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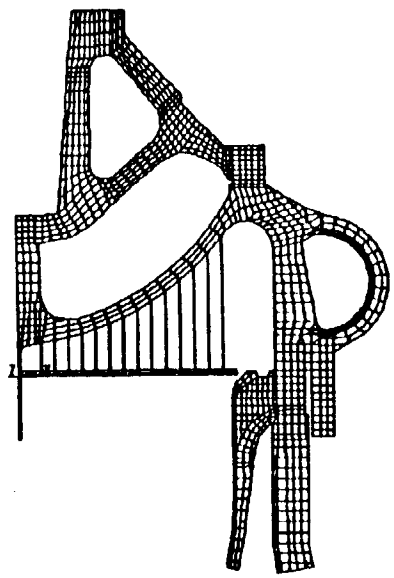
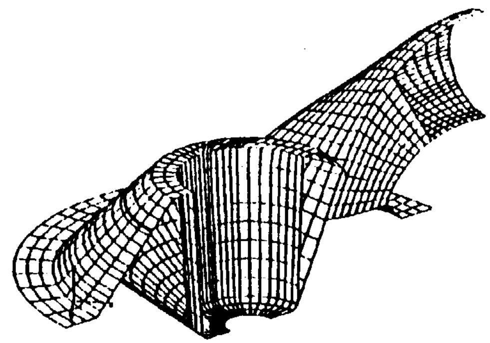
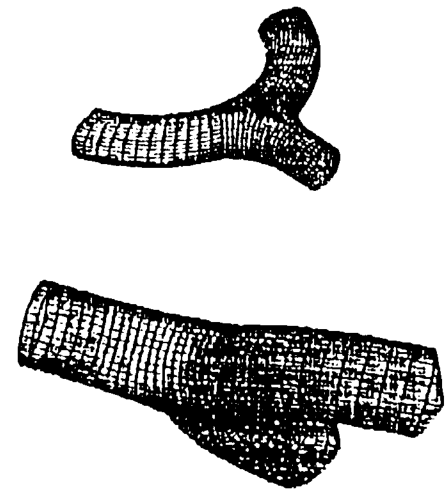
INJECTOR FINITE ELEMENT MODELS



Axisymmetric Model
Injector Assembly



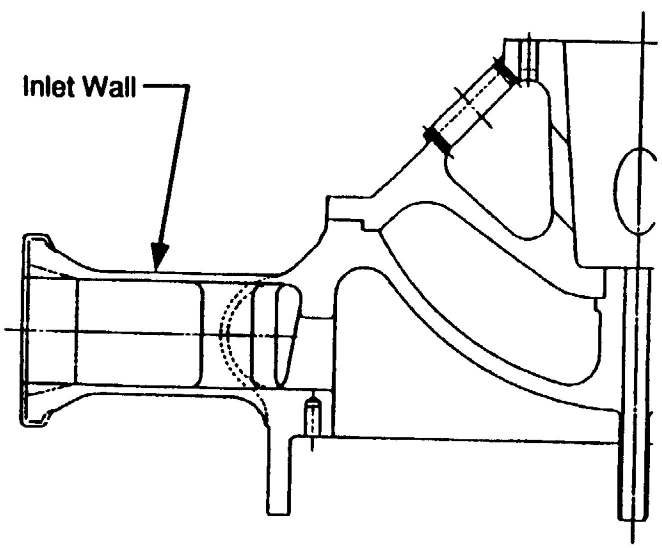
3D Model
LOX Inlet/Dome



3D Model
Fuel Inlet

PRELIMINARY RELIABILITY ASSESSMENT USING PROBABILISTIC ANALYSIS

Fuel Manifold Inlet Wall



DETERMINISTIC SAFETY FACTORS

		(Design Reqm't)
Primary	1.85	(1.5)
High Cycle Fatigue:	1.75	(1.25)
Fracture Mechanics: ($\Delta K_{th}/\Delta K$)	1.33	(1.0)

INJECTOR RELIABILITY ALLOCATION:

R = 0.99997

PROBABILISTIC

Random	Mean	STD
Pressure	2900	290
Thickness	0.350 in.	005 in.
External	120,000 in/lbs	18,000 in/lbs
Vibration Load	19,146	957 lbs
Stress Concen. Factor	1.00	0.05
Ultimate	92,200	4,600 psi
Endurance	27,800	1,390 psi
Modeling	1.0	0.05

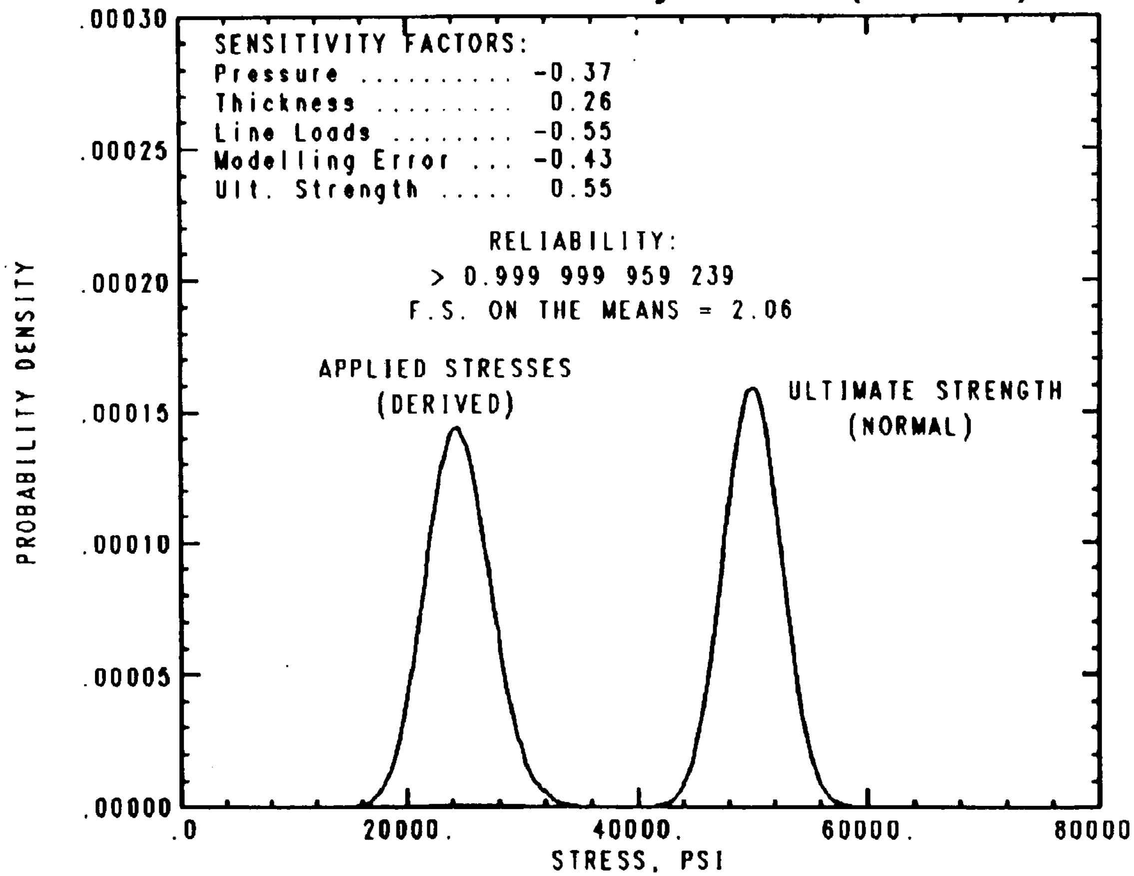
RELIABILITY

Burst $R = 0.9_7$

HCF Crack Initiation $R = 0.9_{13}$

ADP MAIN INJECTOR FUEL INLET PROBABILISTIC ANALYSIS

Failure Mode: Primary Stress
First-Order Reliability Method (Level III)



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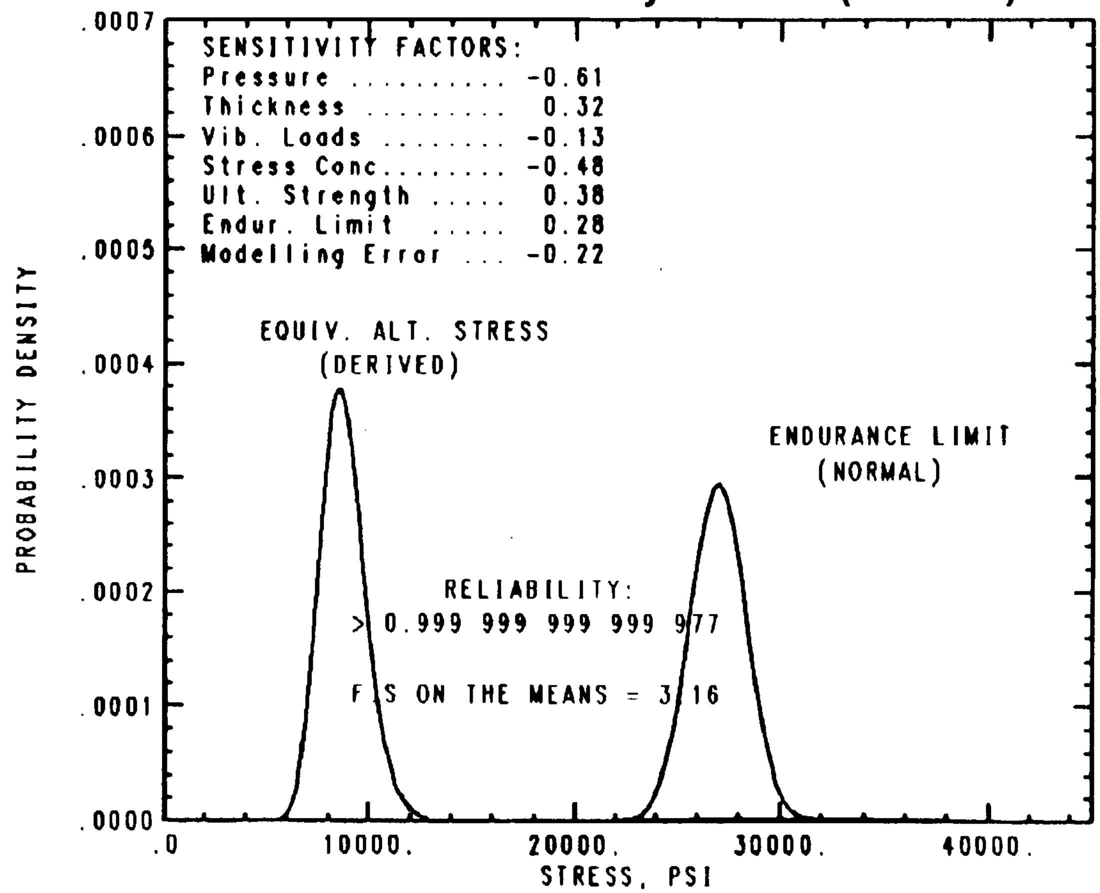
ADP MAIN INJECTOR FUEL INLET PROBABILISTIC ANALYSIS

Failure Mode: High-Cycle Fatigue
First-Order Reliability Method (Level III)



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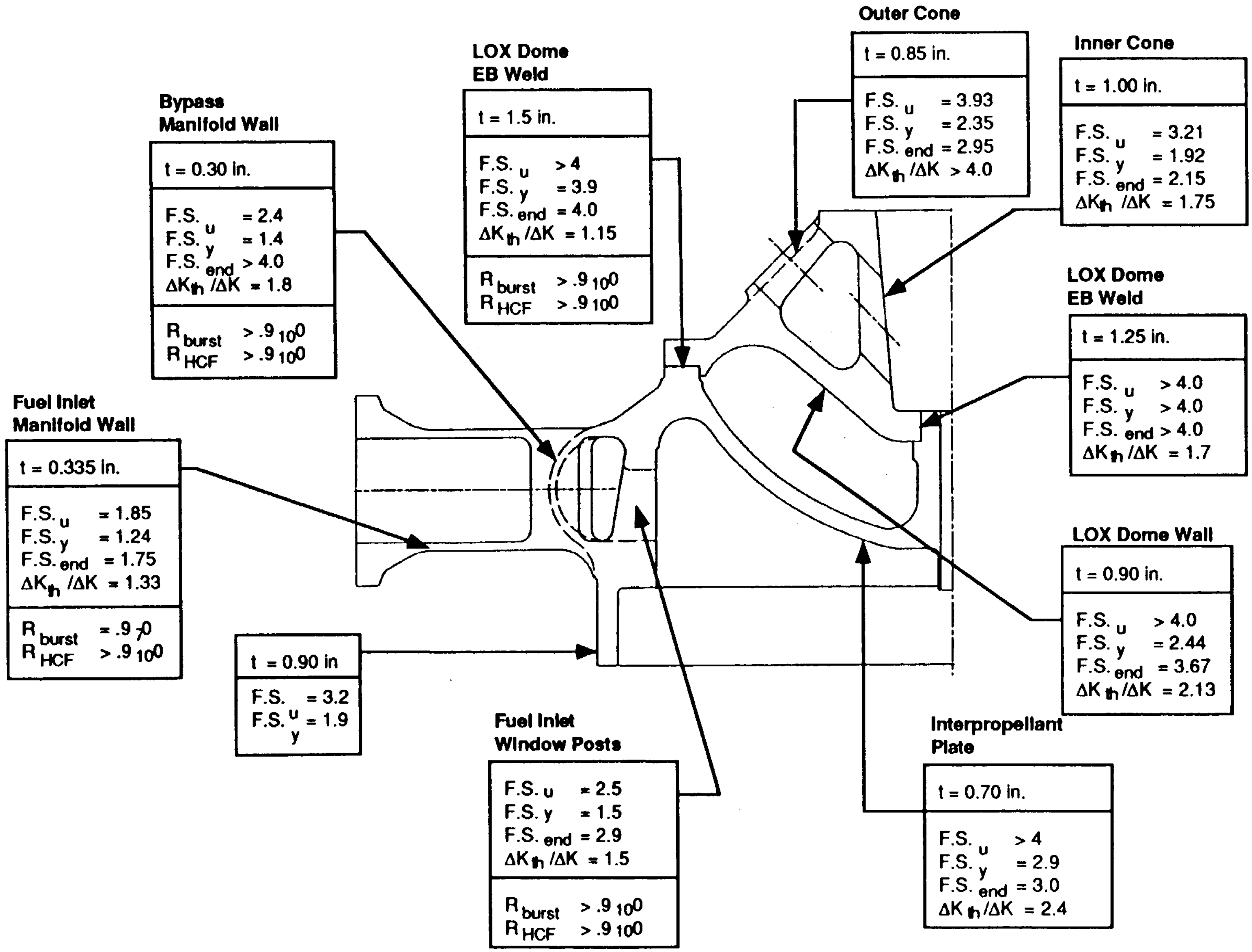
MAIN INJECTOR SAFETY FACTOR AND RELIABILITY SUMMARY



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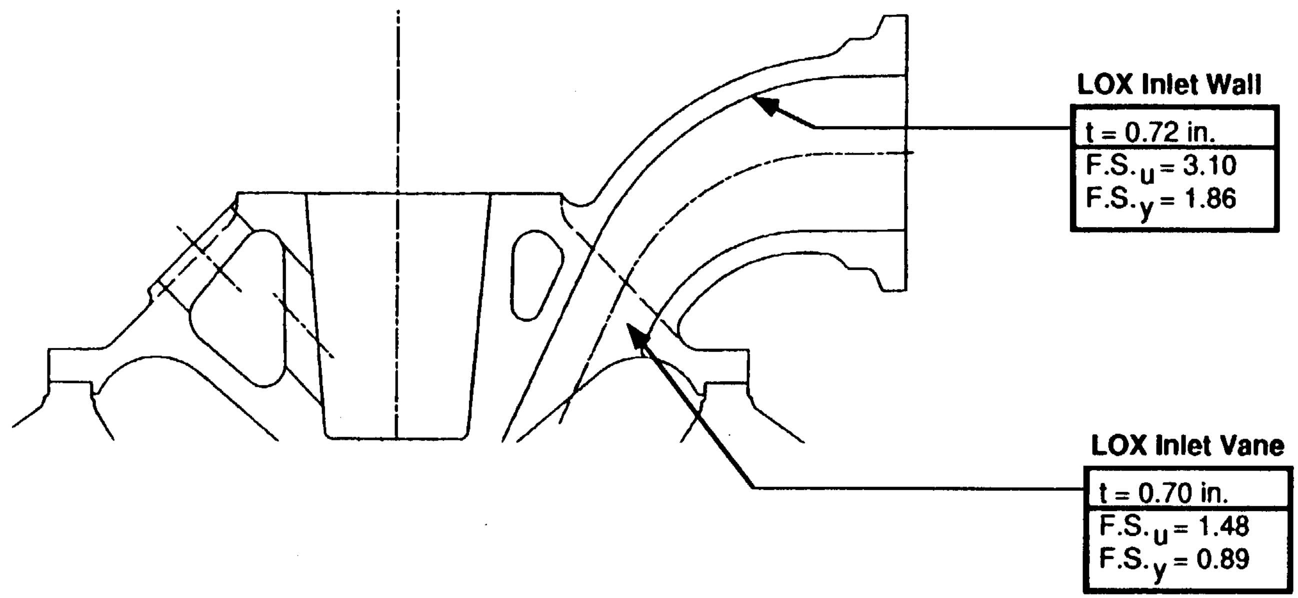
MAIN INJECTOR LOX INLET
Safety Factory Summary



- Safety factors based on primary stress only
- Design changes required to satisfy structural criteria

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HYDROGEN MIXER

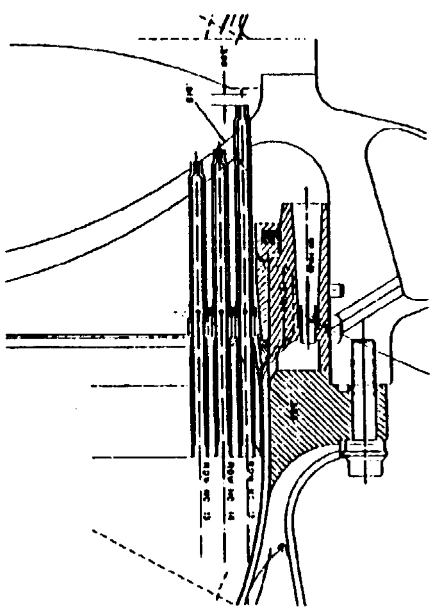
- **Function**
  - Mix combustion chamber coolant discharge and hydrogen bypass flow
  - Minimize overall coolant system pressure loss (jet pump pressure recovery)

INJECTOR/COMBUSTION CHAMBER MIXER SYSTEM

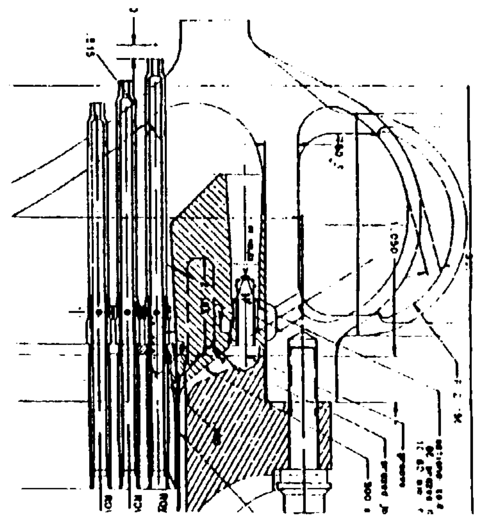
- **Advantages**
  - Reduces combuster weight
    - Combuster coolant flowrate reduced to 20% total fuel flowrate
    - More efficient channel structural configuration
  - Improves combuster fabricability
    - More favorable channel dimensions
    - Lower overall fabrication cost
- **Disadvantages**
  - More complex coolant discharge section

FUEL MIXER DESIGN CONCEPTS

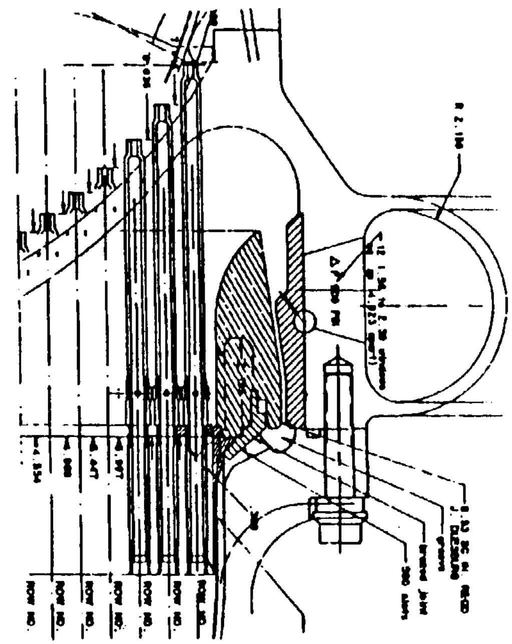
- **Concentric tube ejector jet pump**
- **Modified ejector jet-pump**
  - Discrete holes for bypass flow
- **Cross jets**



Jet Pump



Modified Jet Pump



Cross Jet Concept

PRELIMINARY MIXER PERFORMANCE ANALYSIS

- **Assumptions**
  - Bypass jet diameter 0.05 in.
  - Minimum of 200 + available jet diameters from mixer to fuel sleeve inlet
- **Results/Conclusions**
  - 3% maximum variation in mixture ratio
    - Jet well mixed at fuel sleeve inlet
  - Approximately 20-25% pressure loss recovery

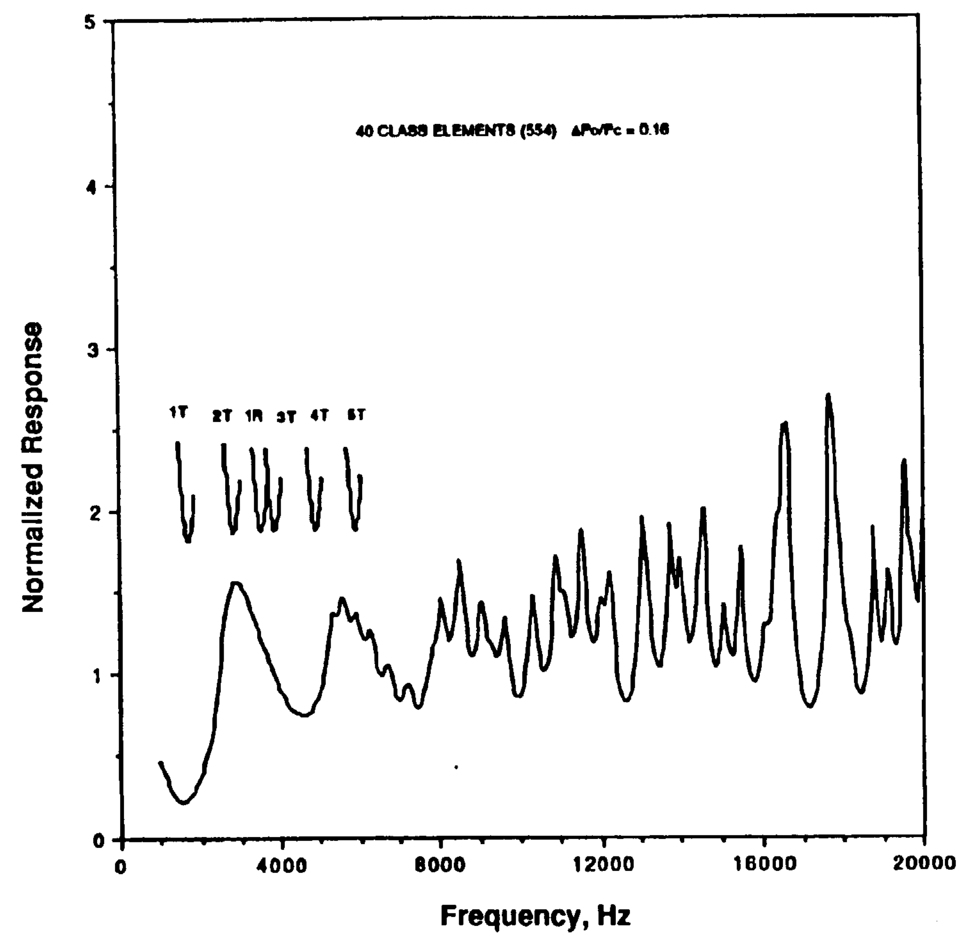
MIXER DESIGN SUMMARY/RECOMMENDATIONS

- **Summary**
  - Established envelope constraints
  - Mixer design concepts allow large degree of flexibility
  - Preliminary mixer performance analysis indicate sufficient mixing at fuel sleeve inlet
- **Recommendations**
  - Evaluate and downselect most promising concepts
  - Laboratory test concepts to select final design

MAIN INJECTOR COMBUSTION STABILITY ANALYSIS

- **Intrinsic instability is predicted**
  - Acoustic aids
    - Use baffle to suppress 1T, 2T, and 1R modes
    - A scaled SSME baffle is recommended based on analysis
    - Acoustic cavities will be used for instabilities>1R mode frequency
    - Provisions for cavities are included in the design

CHAMBER AND INJECTOR LOX POST RESPONSE FOR THE ADP COMBUSTOR

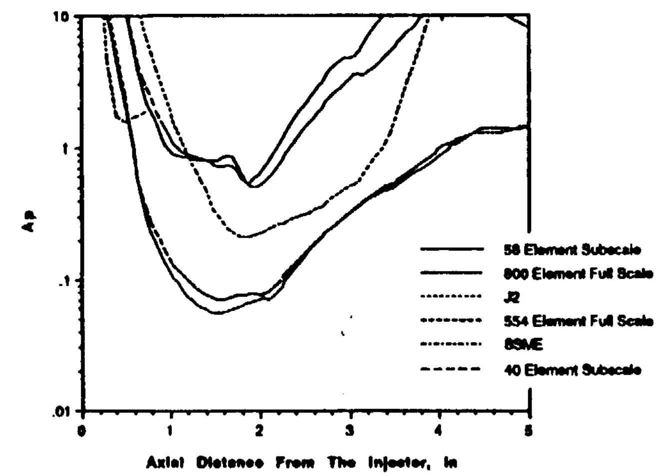


94LS/077-104

ADP INJECTOR DESIGN
Intrinsic Stability Predictions

- Priem analysis was performed for subscale and full-scale designs with CICM to predict overpressure values which will cause instability
- Results are compared to the SSME and J2

Priem Analysis for the 1T Mode



- Bomb testing is planned to determine the high frequency response of the combustion process and to compare to analytical results

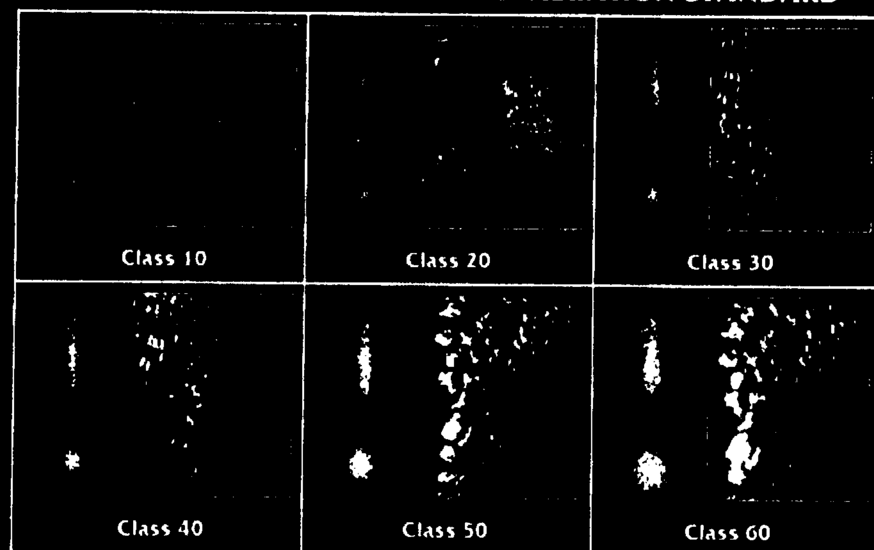
INSPECTION TECHNOLOGIES ASSESSED

- **Casting Quality**
  - Inspection Standards: Radiographic and casting microshrinkage penetrant
  - Computed Tomography: In use for foundry practice development
- **Casting Electron Beam Weld Quality**
  - Ultrasonic Spectral Analysis: Demonstrated effective for weld inspection through thick walled casting (conventional methods failed)
  - Ultrasonic Flaw Classifier: Can discriminate different sized flaws independent of casting attentuation

LOX DOME CASTING INSPECTION

- Penetrant microshrinkage standard allows for direct assessment of shrinkage severity
  - Levels selected adhere to industry practice & Rocketdyne historical acceptance limit experience
  - Penetrant severity levels compliment radiographic acceptance criteria & enhances evaluation of difficult radiographic inspection access areas

PENETRANT MICROSHRINKAGE EVALUATION STANDARD



1. Refer to engineering drawing notes for evaluation technique.
2. Two indications at the left of each grade depict level of concentration permitted.
3. Photograph to the right of each level represents how the condition typically appears on a casting.

Rocketdyne Quality Standard - RD CMS-1

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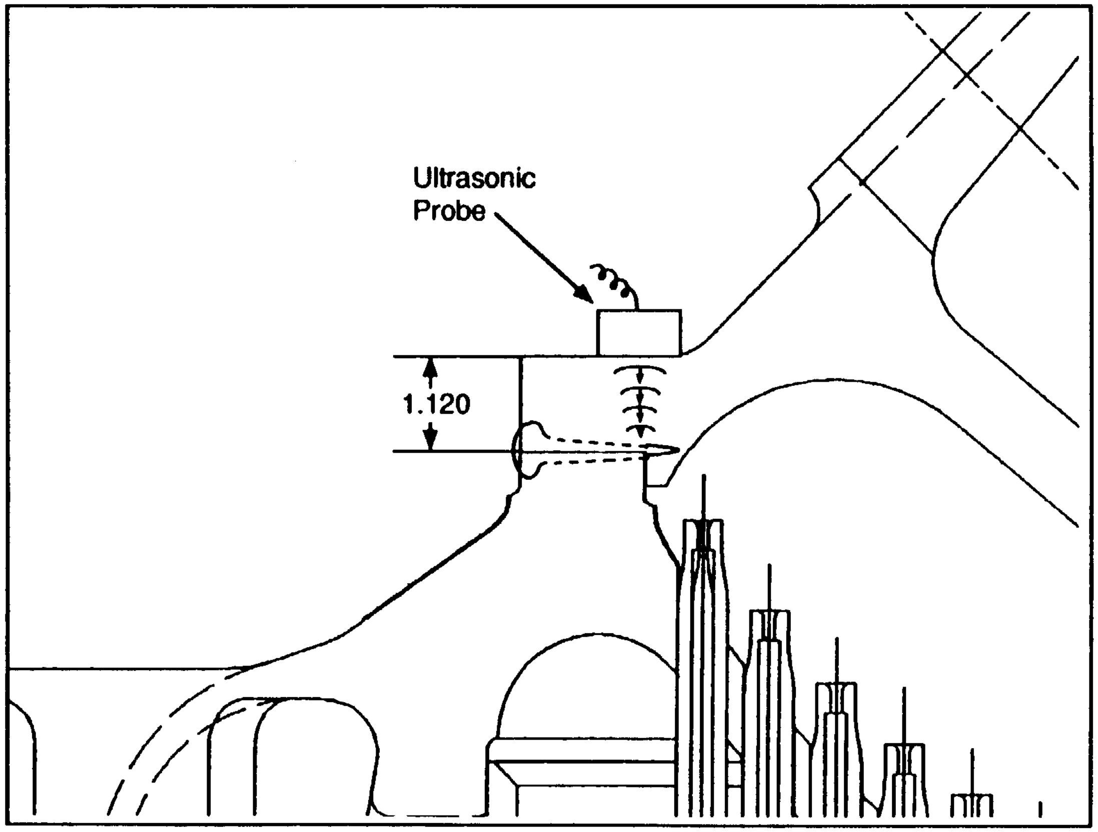
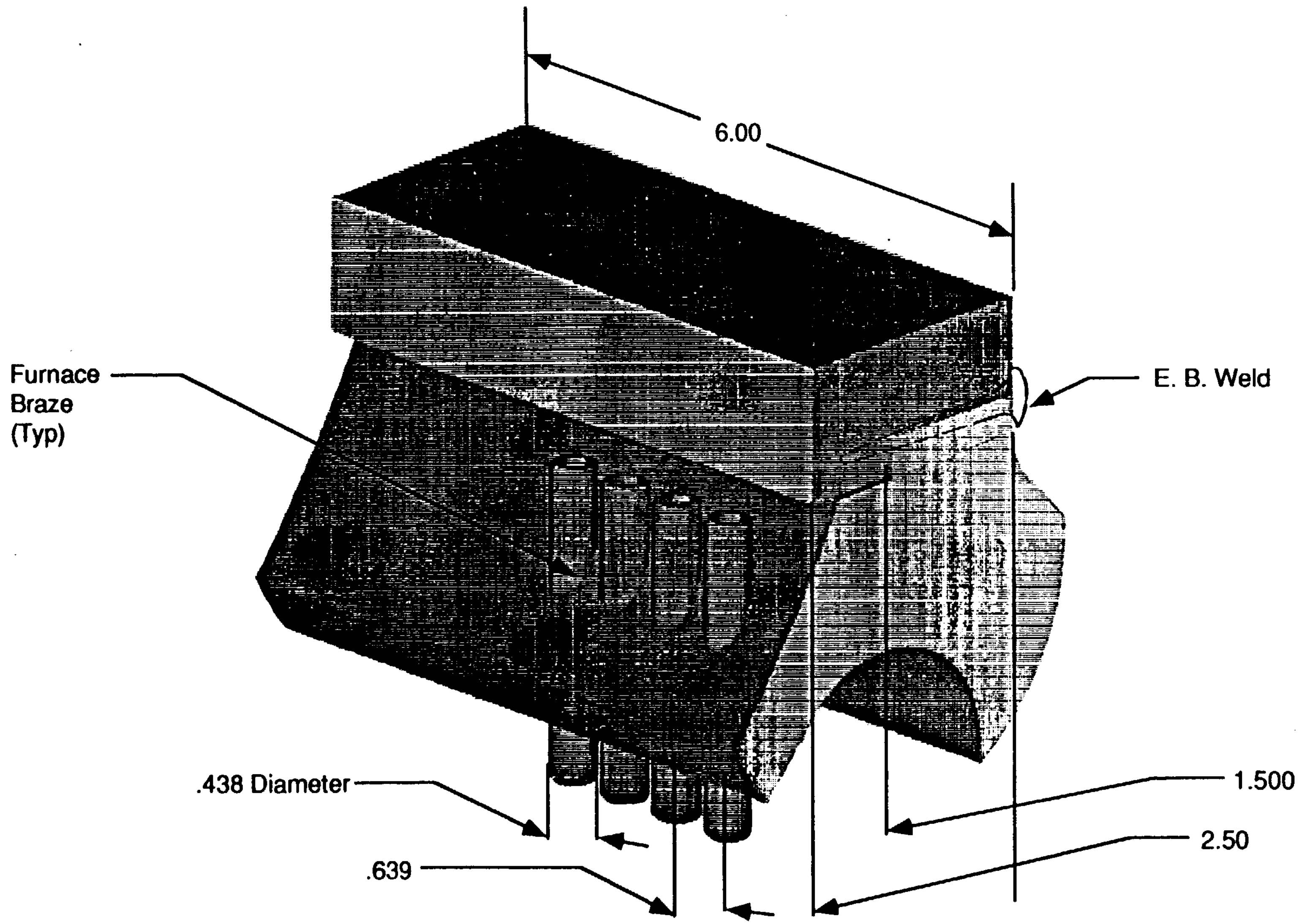
ULTRASONIC TEST SAMPLES

- **Two techniques were tried on cast INCO 625 samples**
  - Image subtraction using pre- and post-weld computer scanning
    - Image subtraction successful
    - Detected all artificial flaws (flat-bottomed holes)
    - Failed to size flaws correctly
  - Waveform feature analysis - analyzing features of the reflected sound
    - System taught what a flaw looks like thru a feature classifier
    - All artificial flaws were detected
    - All flaws were sized correctly
- **Requirements for a 90/95 reliability program for waveform feature analysis being determined**

WELD ULTRASONIC INSPECTION



ELECTRON BEAM WELD SAMPLE



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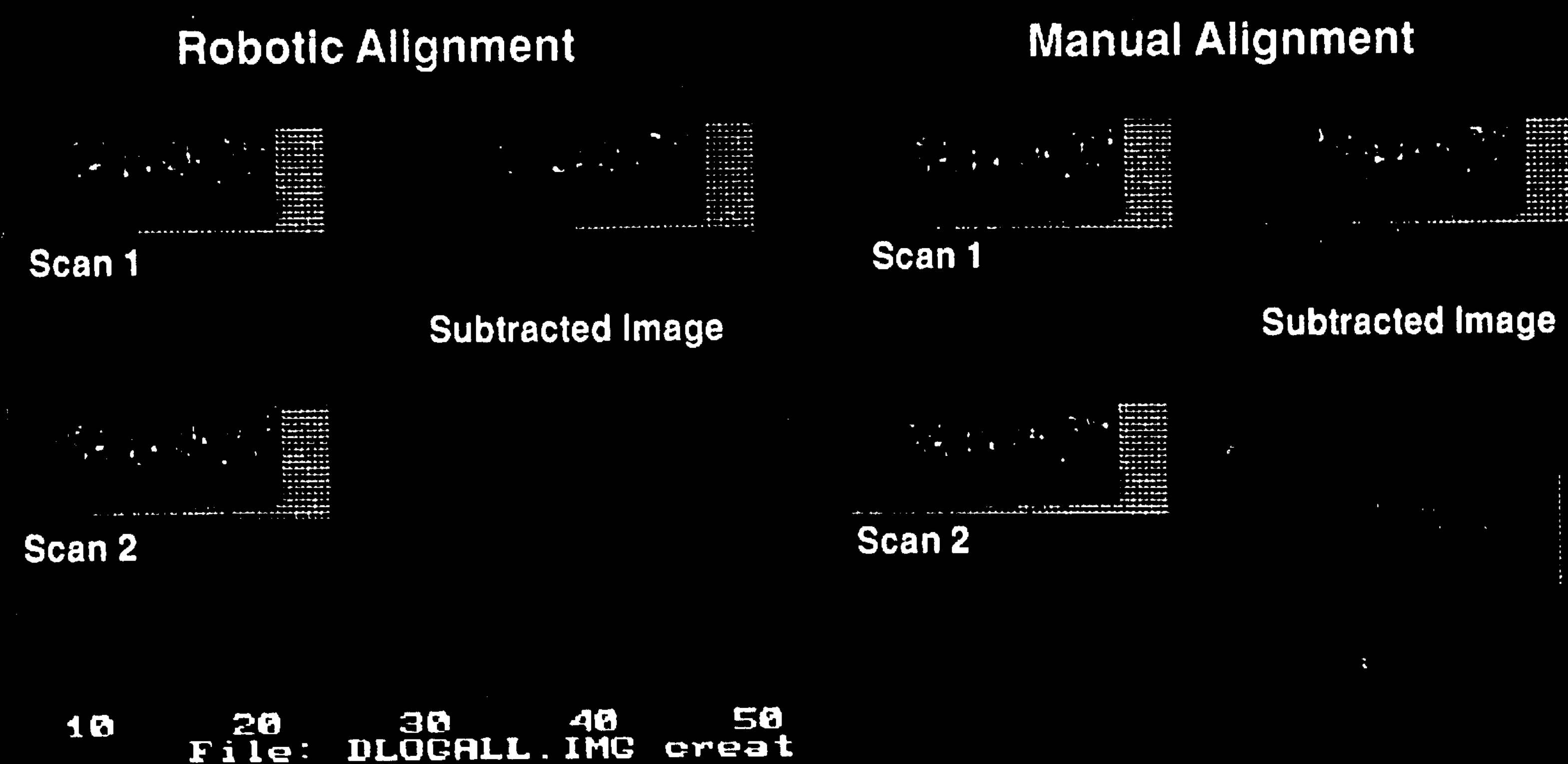
CAST WELD JOINT ULTRASONIC INSPECTION
CAL DATA APPROACH

- Image overlay & subtraction negates cast material influence when sufficient alignment points are defined
  - Existing hardware features are acceptable for this purpose
- Scans of artificial flaws will be performed to prove/disprove concept



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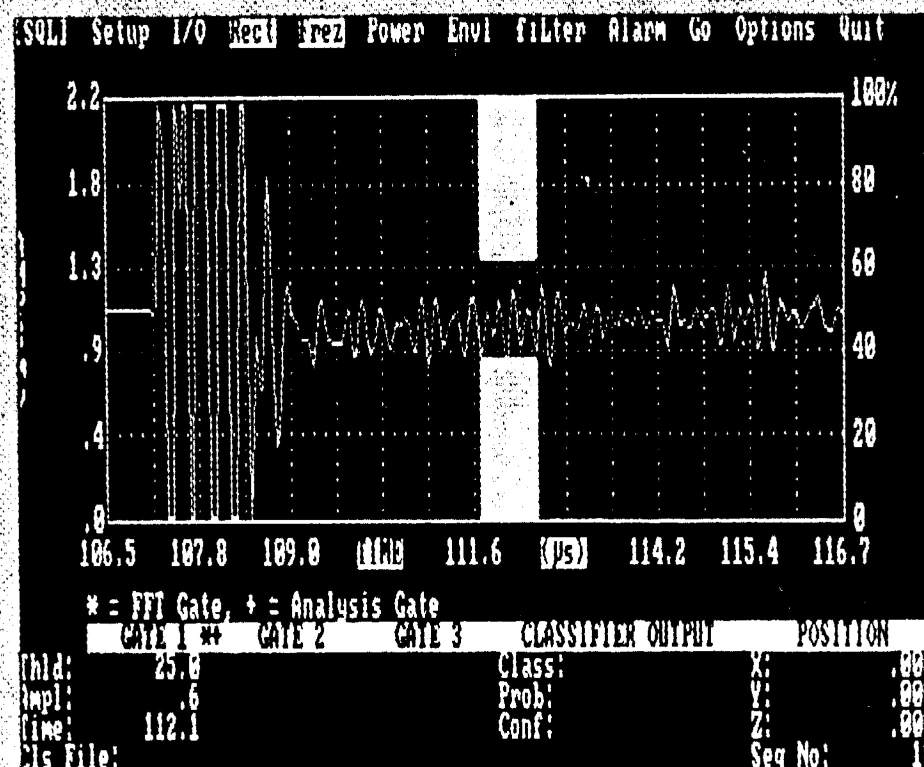
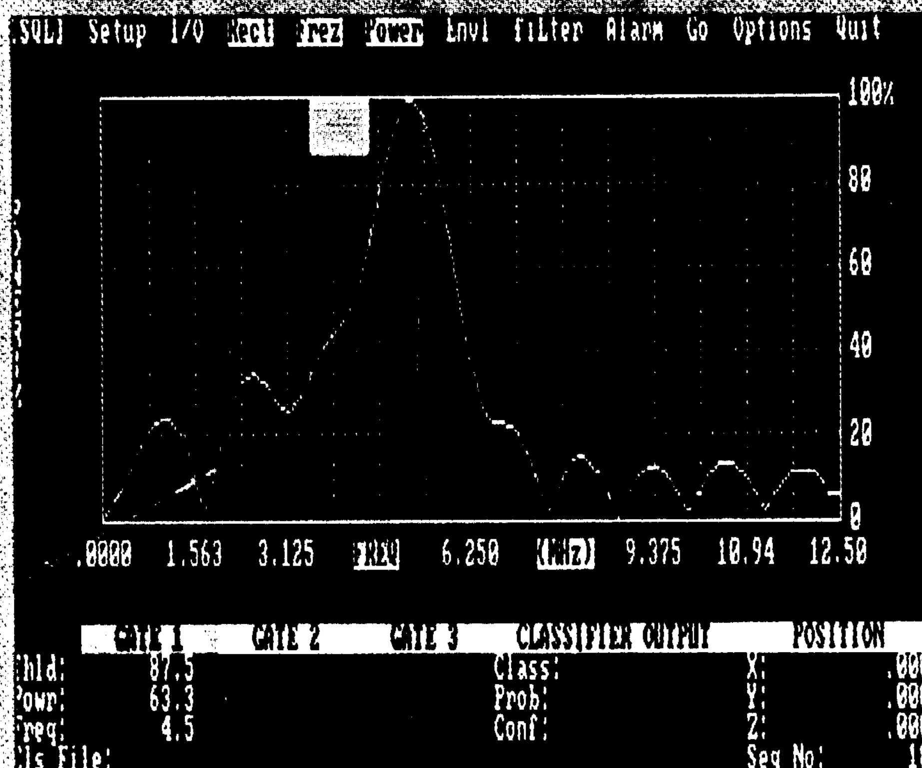
CAST WELD JOINT ULTRASONIC INSPECTION
INTEK APPROACH

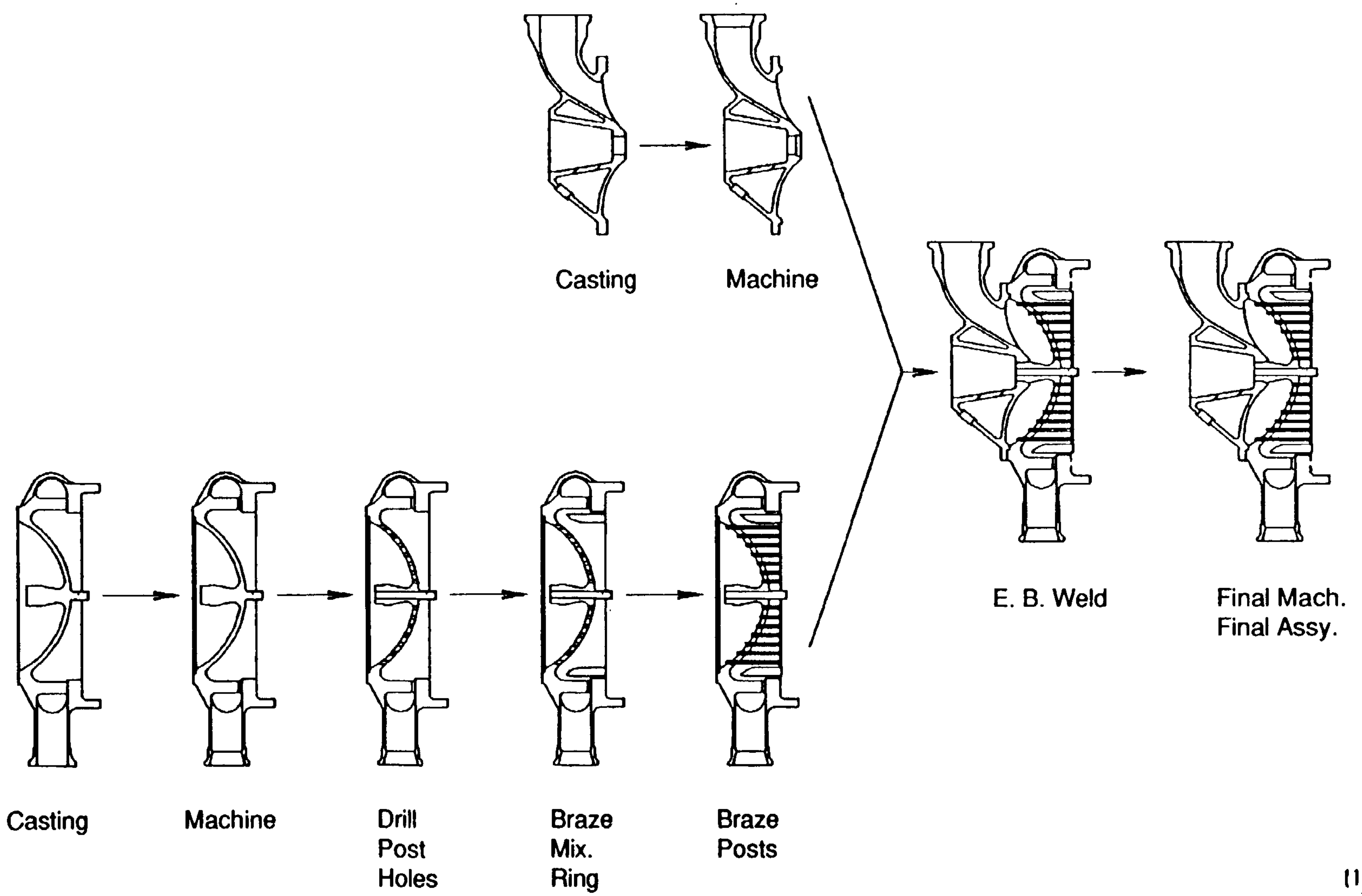


CAST WELD JOINT ULTRASONIC INSPECTION
INTEK APPROACH

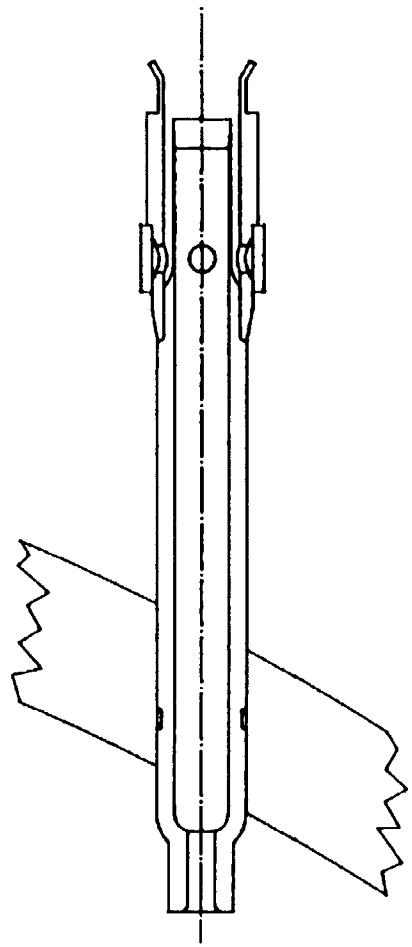
- [illegible] analysis profile of [illegible] in. diameter artificial flaw
- Highlighted area is flaw gate
- All [illegible] in. flaws were identified as identical by the classifier



INJECTOR ASSEMBLY FAB SEQUENCE



MANUFACTURING STEPS
BRAZED ASSEMBLY

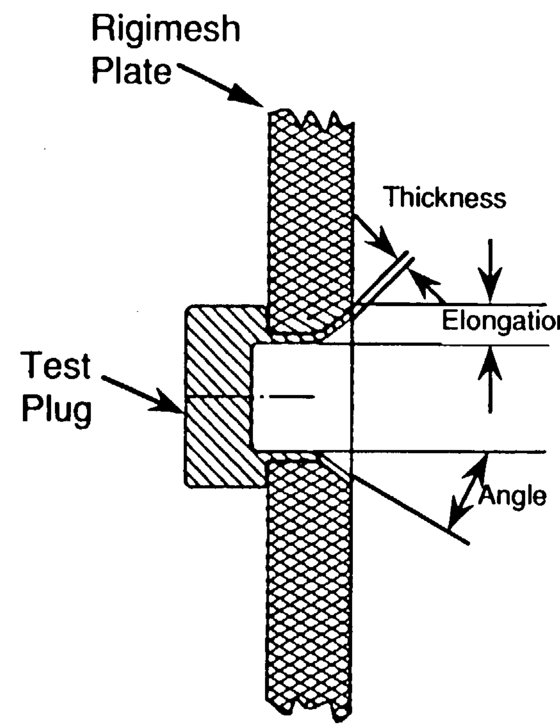


Manufacturing Steps

1. Drill interpropellant plates
2. Ni plate interpropellant post holes
3. Assemble post assemblies into interpropellant plate
4. Furnace braze
5. Inspect braze joint: visual and leak check

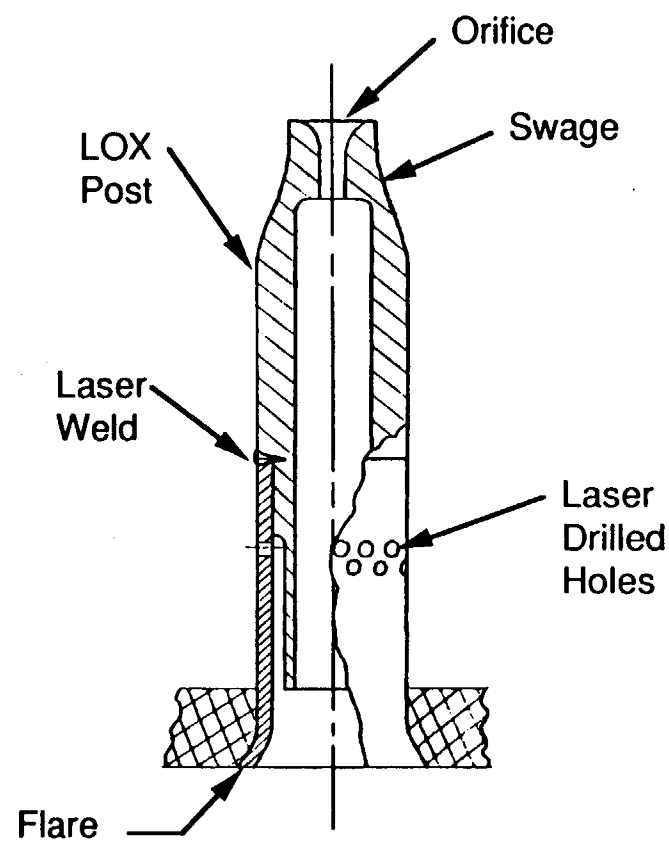
INJECTOR
Low Cost Fab Status

- **Fuel sleeve flare**
  - Fuel sleeve samples in work at vendor
  - Test uses Taguchi methodology
    - Material
    - Wall thickness
    - Elongation
    - Flare angle
  - Results will provide joint strength vs. process robustness
- **Testing was not performed**

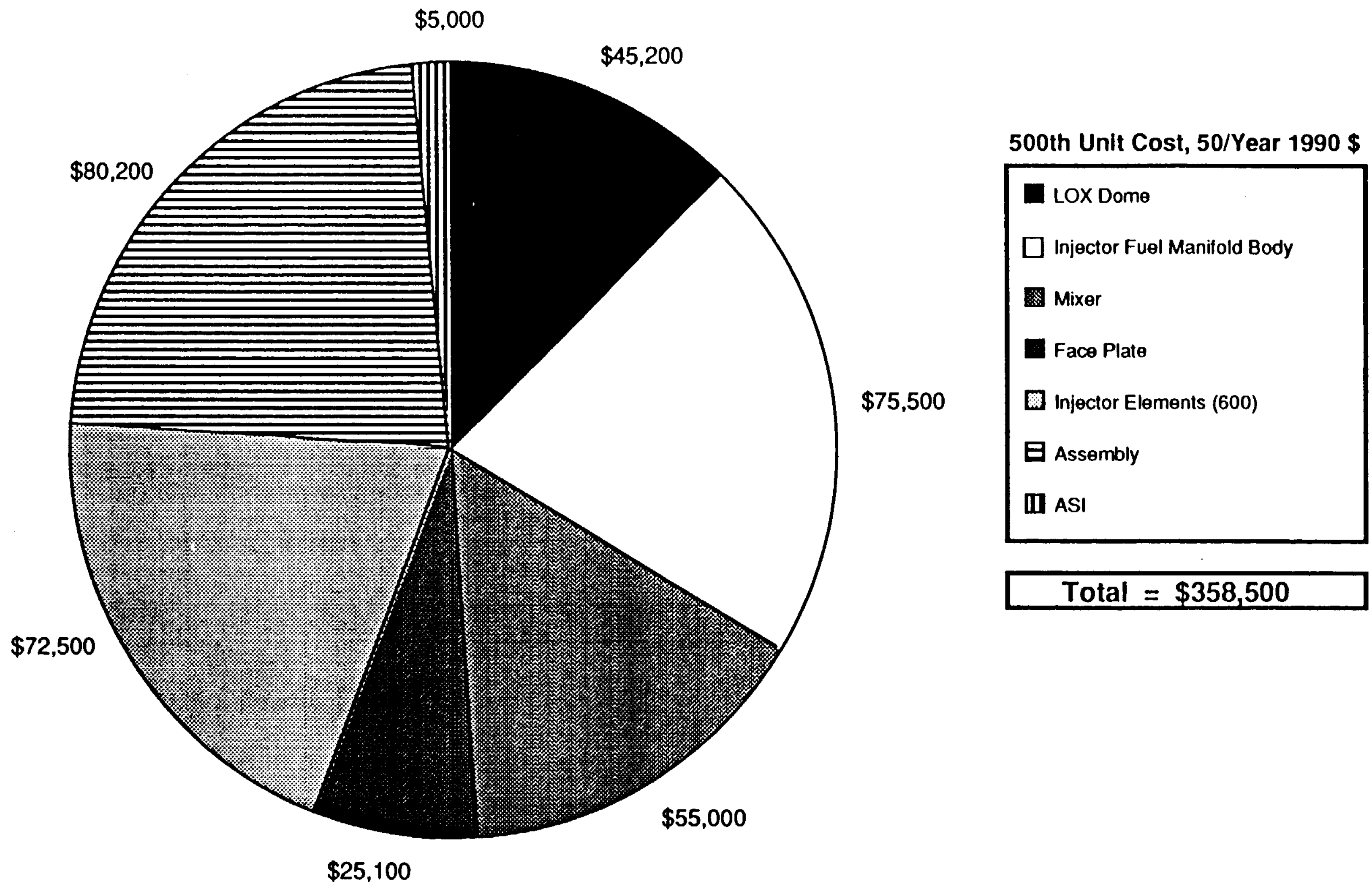


INJECTOR
Low Cost Fab Status

- **Low cost element design**
  - Processes
    - Tube stock (LOX post/fuel sleeve)
    - Swage LOX post/drill orifice
    - Laser drill fuel sleeve holes
    - Laser weld sleeve to post
    - Flare fuel sleeve
  - Target cost: $55/element
  - Post swaging process tested and report written



INJECTOR 500TH UNIT BREAKDOWN
June 1990



INJECTOR COST SENSITIVITIES

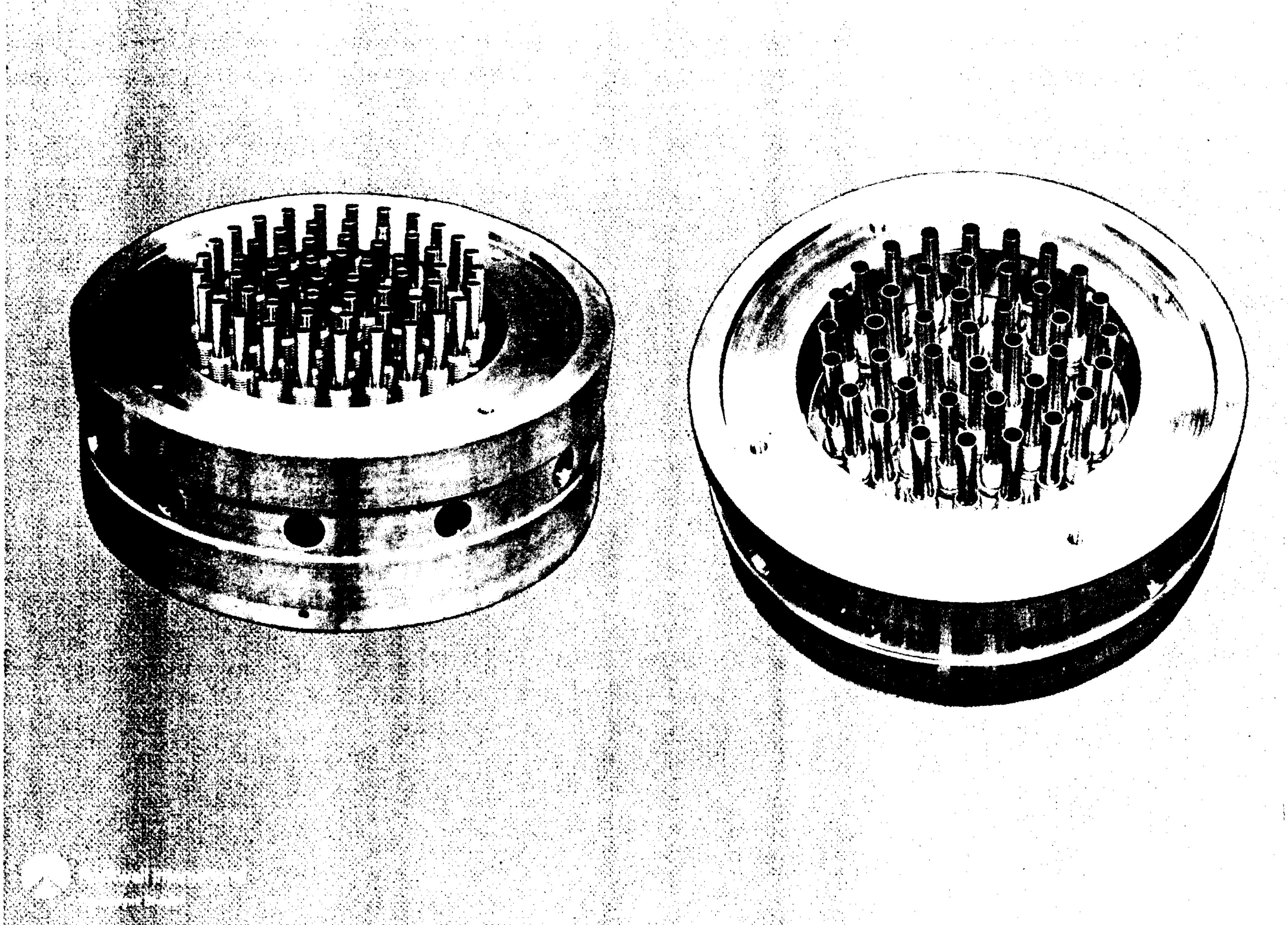
Part	Nominal (600 Elements)	Minimum (372 Elements)	Maximum (800 Elements)
LOX Dome	45,200	41,700	52,200
Injector Lower Body (IPP)	75,500	64,400	89,400
Mixer	55,000	10,000	100,000
Accoustic Cavity	0	0	5,700
Face Plate	25,100	22,100	27,700
Injector Elements	72,500	40,500	141,700
Assembly/Inspection	80,200	78,600	133,900
Baffles	0	0	28,500
ASI	5,000	5,000	10,400
Total	**359,000**	**262,000**	**590,000**

2.2.3 Subscale Injectors

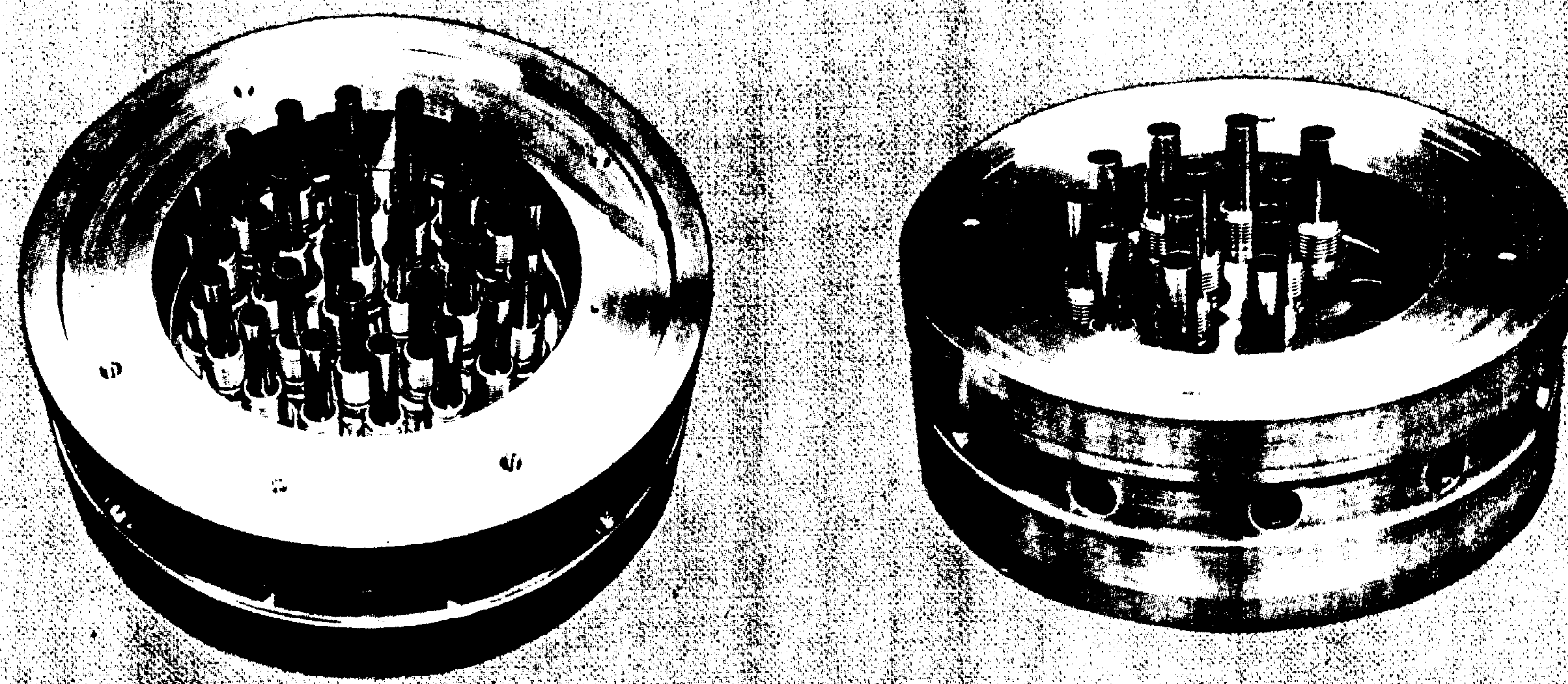
SUBSCALE INJECTORS

- **Objectives**
  - Determine performance vs. number of elements curve
  - Evaluate heat transfer characteristics
  - Obtain stability information
- **Approximately 30 tests were planned**
- **Fabricated 4 injectors with different element densities**
  - 58 elements
  - 40 elements
  - 28 elements
  - 15 elements

58 & 40 ELEMENT INJECTORS



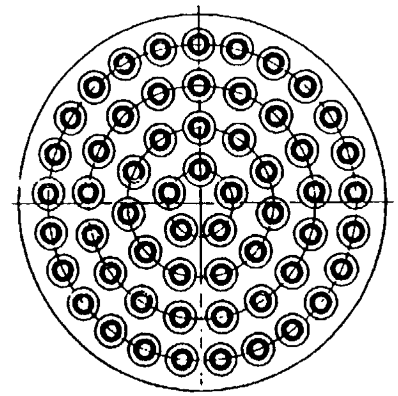
28 & 15 ELEMENT INJECTORS



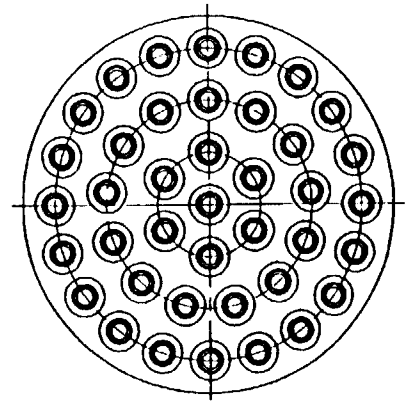
INJECTOR CONFIGURATIONS

- **Face patterns**
  - **Objectives**
    - Same outer row element spacing as full-scale
    - Same wall-to-outer row distance as full-scale
    - Same element density as full-scale
    - Due to size differences, resulting patterns are best compromise of objectives
  - **Elements**
    - All injectors use the same element configuration
    - The three coarsest pattern injectors will have provisions for LOX swirl

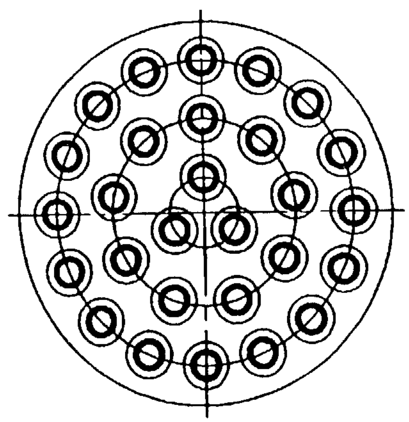
SUBSCALE INJECTOR FACE PATTERN



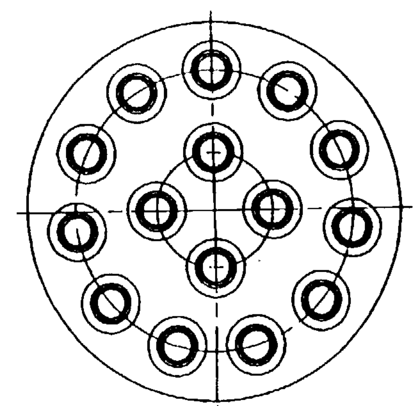
58 Elements
795 Elements Full-Scale



40 Elements
550 Elements Full-Scale



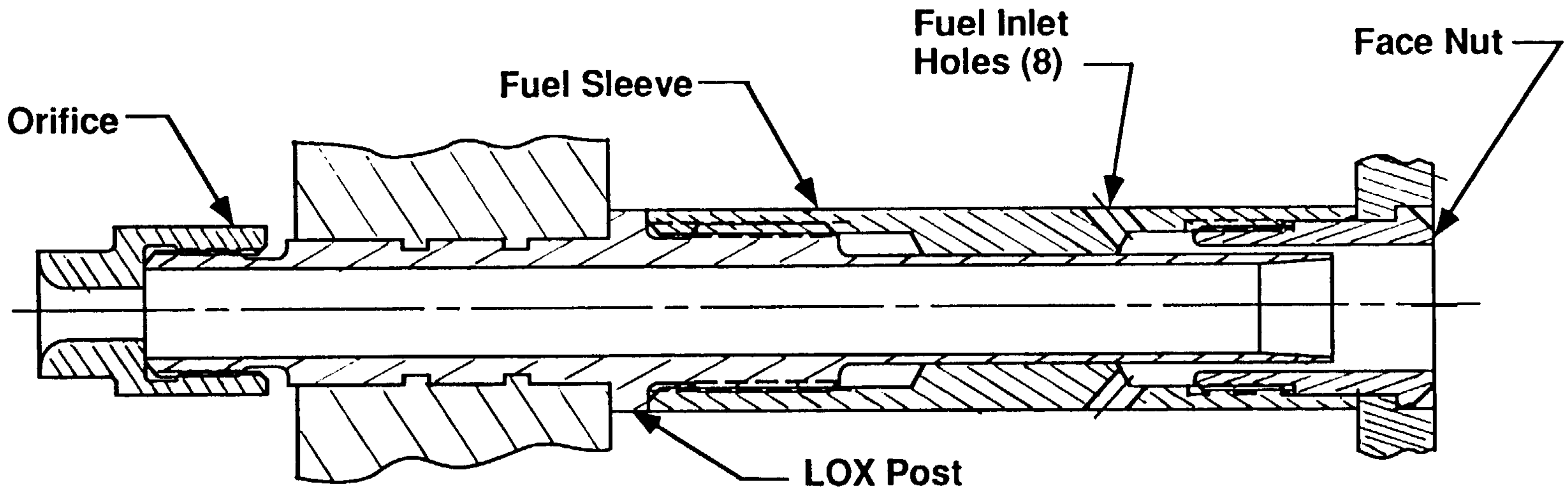
28 Elements
375 Elements Full-Scale



15 Elements
210 Elements Full-Scale

SUBSCALE INJECTOR

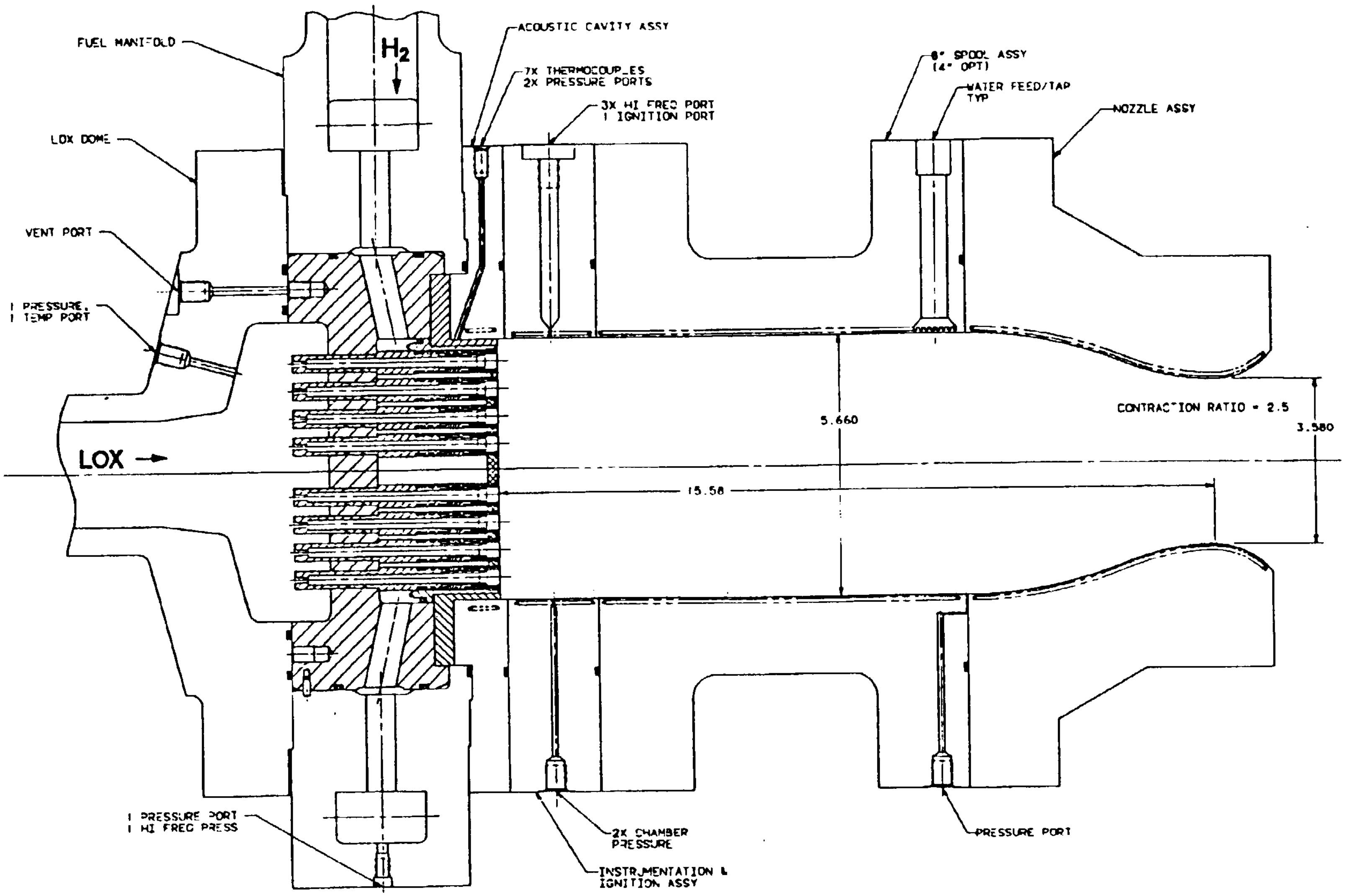
Typical Element Configuration



SUBSCALE CALORIMETER COMBUSTOR HARDWARE FABRICATED

- **For use in testing subscale injectors**
  - Provides heat flux profile of combustor specific to injector tests
  - Obtain injector performance and stability characteristics
- **Parts fabricated**
  - (1) 4" calorimeter combustor spool (7RO38366)
  - (1) 8" calorimeter combustor spool (7RO38367)
  - (1) 8" axial calorimeter combustor spool (7RO38368)
  - (1) calorimeter injector/combustor transition spool (7RO38362)
  - (1) instrumentation injector/combustor spool (7RO38378)
  - (1) calorimeter throat nozzle (7RO38370)

SUBSCALE COMBUSTOR
Typical Assembly



SUBSCALE INJECTOR STATUS

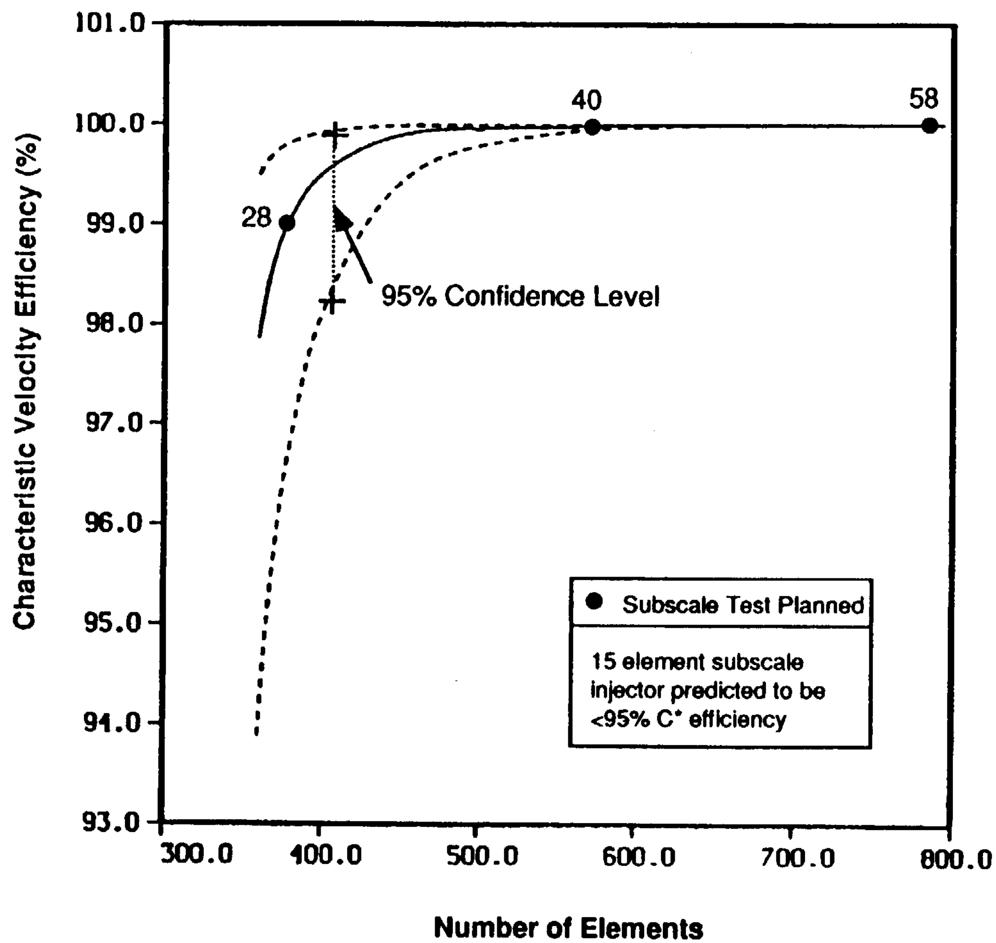
- **Fabrication of all injectors complete**
  - Proof and leak inspections still required
- **LOX dome and fuel manifold will require some machining for cryogenic seals**

INJECTOR ELEMENT SELECTION BASED ON SUBSCALE TESTING

- **Selection of injector geometries based on:**
  - Performance analysis trends
  - Manufacturing costs:
    - Fewer number of elements - lower cost
    - Casting limits
  - Maximum number of elements for chamber area
  - Injector fuel Δ pressure
  - Stability considerations

- **Subscale/full-scale element number conversion:**
  - 58/794 elements
  - 40/552 elements
  - 28/378 elements
  - 15/212 elements

PREDICTED PERFORMANCE VS. ELEMENT DENSITY



STABILITY ANALYSIS CONCLUSIONS

- Subscale combustor is predicted to be spontaneously stable without acoustic aids
- Intrinsic instability is predicted at ~60% peak-to-peak overpressure in subscale designs
- All analyses will be conducted to aid in the full-scale design
- Stability testing is recommended to aid in the full-scale design with subscale validation

2.2.4 - MAIN INJECTOR RESULTS

- Completed Preliminary Design Review and detail drawing of fuel manifold/body
- Nearly completed design and analysis of LOX dome
- Fuel mixer concept designed and analyzed
    - Final mixer not selected/detail analysis not complete
- LOX post swage process tested and report written
- Four subscale injectors design and fabricated
    - Proof and leak testing required
- Injector summary report completed

2.3 COMBUSTION CHAMBER

The SSME main combustion chamber (MCC) was used to determine cost and reliability drivers since the operating requirements are similar and data was readily available. As with the injector, the majority of the costs were due to a high number of machined forgings welded together. The reliability drivers were compiled from SSME MCC Unacceptable Condition Reports (UCR's). The single largest problem was due to injector/chamber compatibility (hot gas wall roughening and cracking). Other significant areas include welding and electroplated bond line defects.

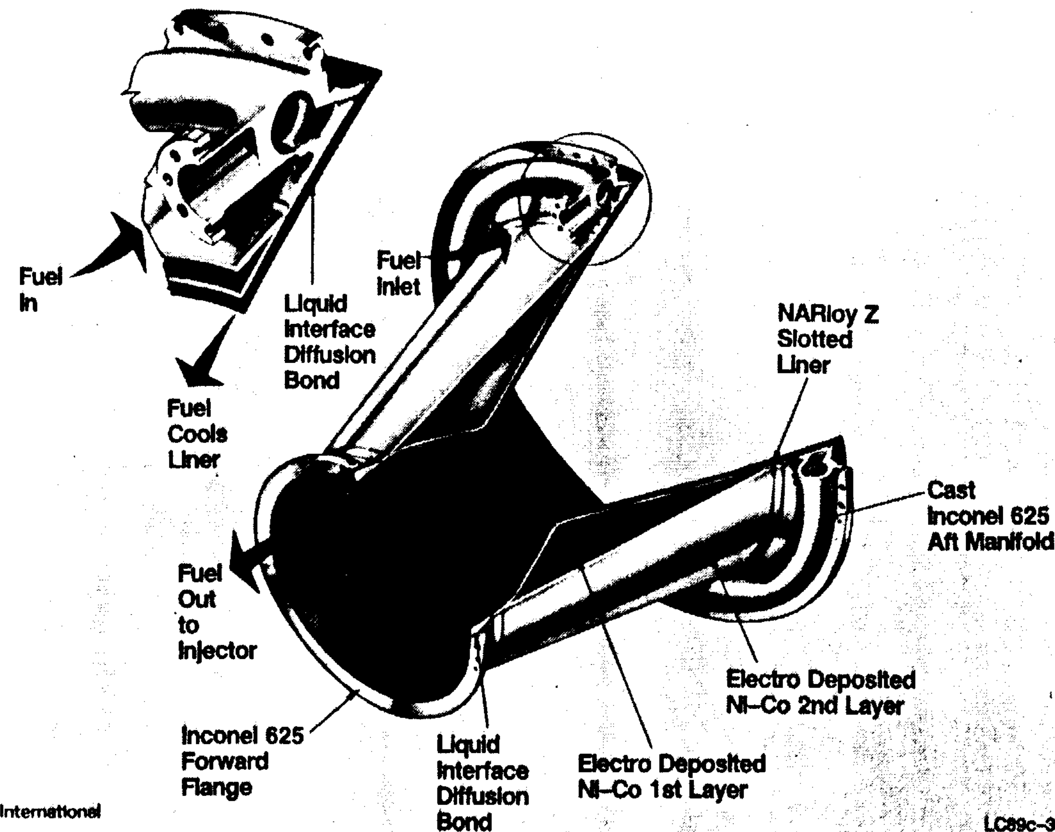
To improve the cost and reliability, 51 combustion chamber concepts were brainstormed and reviewed. The most promising concept to meet the program goals was a chamber that used a single investment casting for the structure and a vacuum plasma sprayed (VPS) liner. This concept required significant material and process development as well as scaling the processes to make a full size combustion chamber. Since the required development would entail significant risk, the second most promising concept was carried in parallel. This concept utilized a wrought material liner diffusion bonded (LIDB) to a forward flange and aft fuel manifold with a high strength electrodeposited nickel-cobolt primary structure. This concept required less development and therefor could be utilized if development problems ocurred with the VPS liner concept.

Both concepts had far fewer parts than on the SSME MCC and would inherently be more reliable and less costly. The charts that follow detail the work associated with the combustion chamber design effort as listed below:

- 2.3.1 Concept Selection
- 2.3.2 Design and Analysis
  - LIDB and VPS Design Configurations
  - Structural and Reliabiltiy Analysis Summary
  - Aerothermal Analysis
  - Cost Summaries
- 2.3.3 JBK-75 Structural Castings
- 2.3.4 VPS Chamber Material/Process Development
- 2.3.5 Combustion Chamber Results

2.3.1 Concept Selection

BASELINE — 1A COMBUSTION CHAMBER



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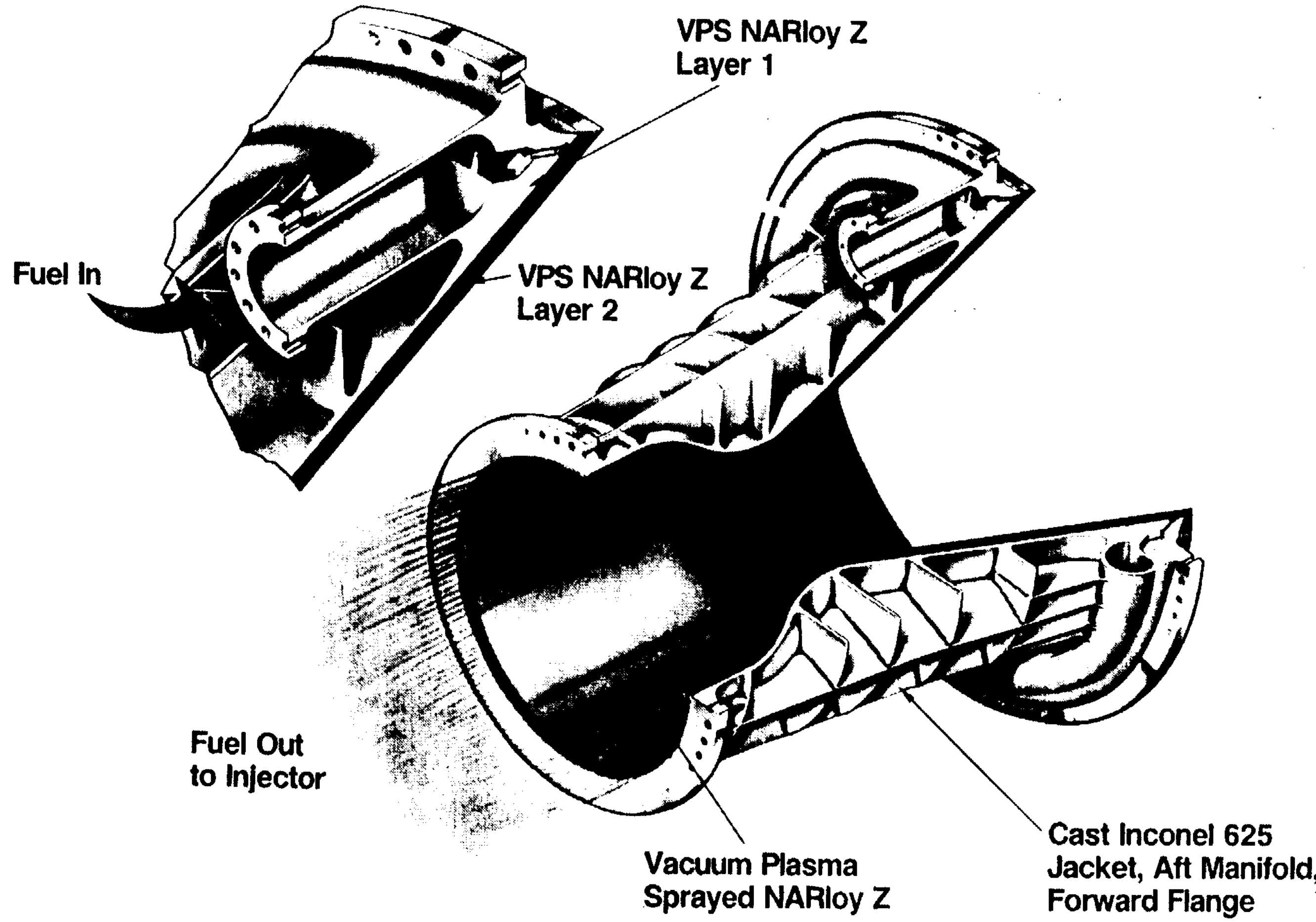
BASELINE — 1B COMBUSTION CHAMBER

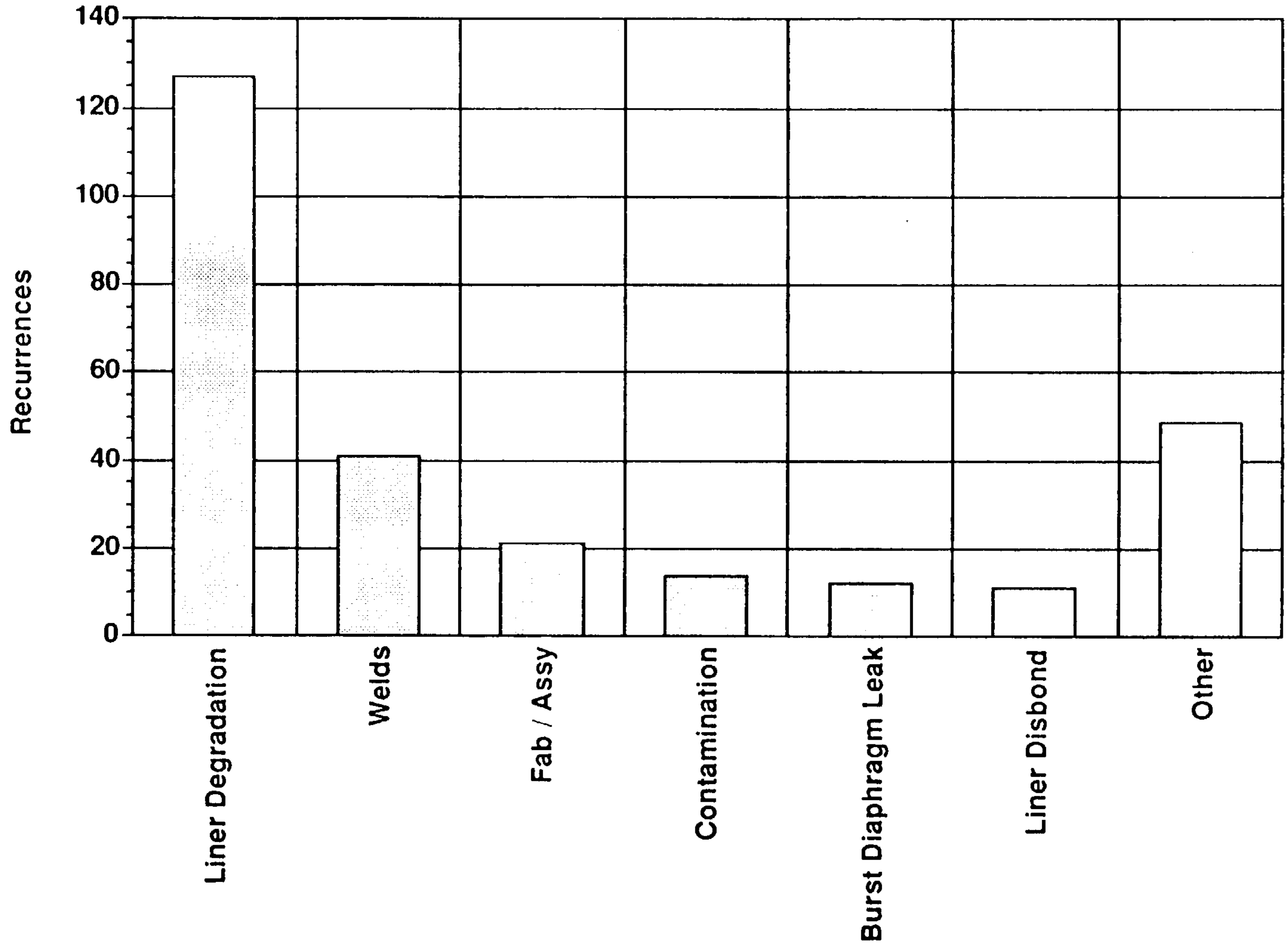


COMBUSTION CHAMBER
COST DRIVERS

- **SSME MCC Costs:**
  - Liner - 6%
    - Cast, forged, spun, slotted
  - Liner closeout - 13%
    - Electroformed copper and nickel
  - Manifolds - 31%
    - Forged, machined, welded
  - Structure - 51%
    - Forged, machined, welded
- **SSME MCC Reliability Concerns:**
  - Hot gas wall surface roughening
  - Hot gas wall cracks
  - Welding defects
  - Inco 718 hydrogen embrittlement
  - Bond line failure

COMBUSTION CHAMBER RELIABILITY DRIVERS SSME MCC UCR DATA

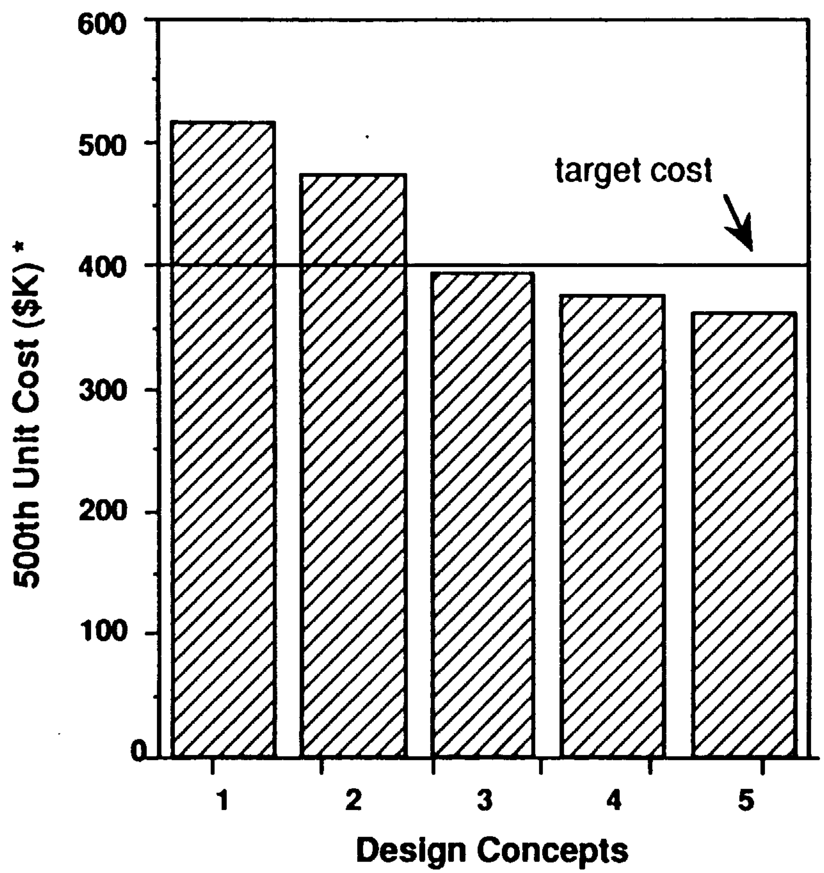
Total reviewed: 275 (1/79 - 6/90)



51 CHAMBER CONCEPTS BRAINSTORMED

Type	Concept Numbers	Description
LIDB chambers	1A, 5, 5A, 8, 12, 24, 29, 30	Variations on liner: cast and VPS. Variation on cast materials: JBK-75, cast 321 Cres. Variations on forming grooves: chem milling and EDM.
Cast jacket with VPS liner	1B, 10, 25, 27, 28, 32, 36	Variations include: fins, JBK-75 and 321 Cres cast jacket, brazed plate and VPS hot gas wall, EDM variable width channels
Transpiration cooled	3, 9, 9A, 17, 18, 34, 38	Stacked platelets, porous liners attached with fasteners, EB weld, brazed, porous tubes
Refractory metal chambers	6, 14, 15C, 16C	Liners, tubes
Metal tubes	2, 13, 15A, 15B, 16A, 16B, 37	Copper, NARloy-Z, brazed to cast jacket, VPS or HVS joined
Thermal barriers	19, 20, 21A, 21B, 21C, 22, 23, 26C, 26D	Zirconium oxide, carbon/carbon liner
Mixed regen/transpiration cooled/ film cooled designs	4, 7, 11A, 11B, 26A, 26B, 31, 33, 35	Combinations of porous and solid metal, film cooled types

COMBUSTION CHAMBER COST COMPARISON



* Assumed 50 units per year, semi-automated manufacturing

LIDB concepts

1: wrought liner,
ED Ni-Co closeout

2: wrought liner,
VPS closeout

Integral cast jacket concepts

3: HIP cold wall,
VPS hot wall

4: VPS cold & hot walls

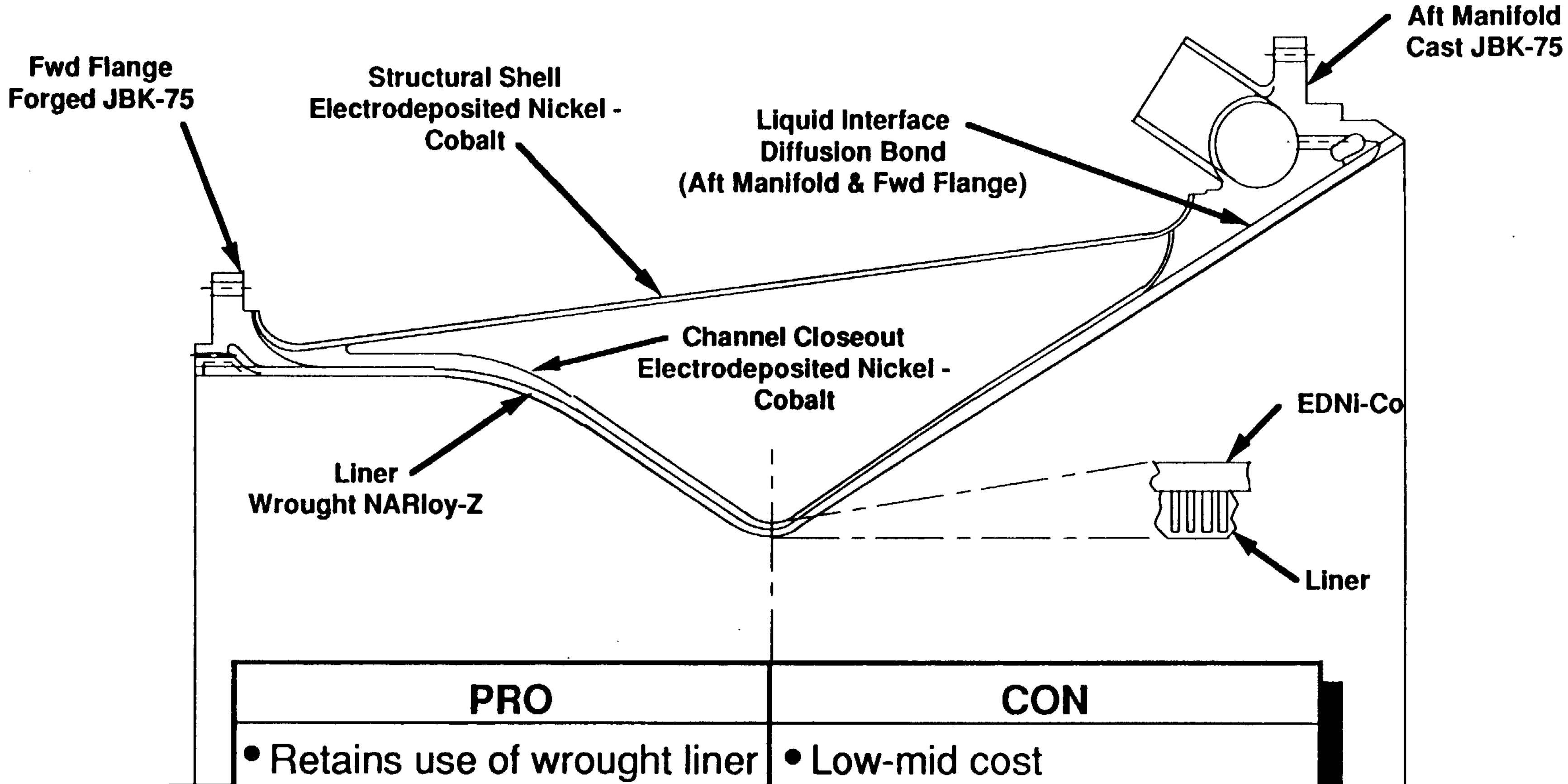
5: VPS cold & hot walls,
hobbed channels

TRADE STUDY CONCLUSIONS
October 1989

- **LIDB/EDNi-Co design should be continued based on a risk-weighted evaluation**
  - JBK-75 for manifold and flange
    - Matches thermal expansion rate of NARloy-Z
    - Offers higher strength and reduced weight

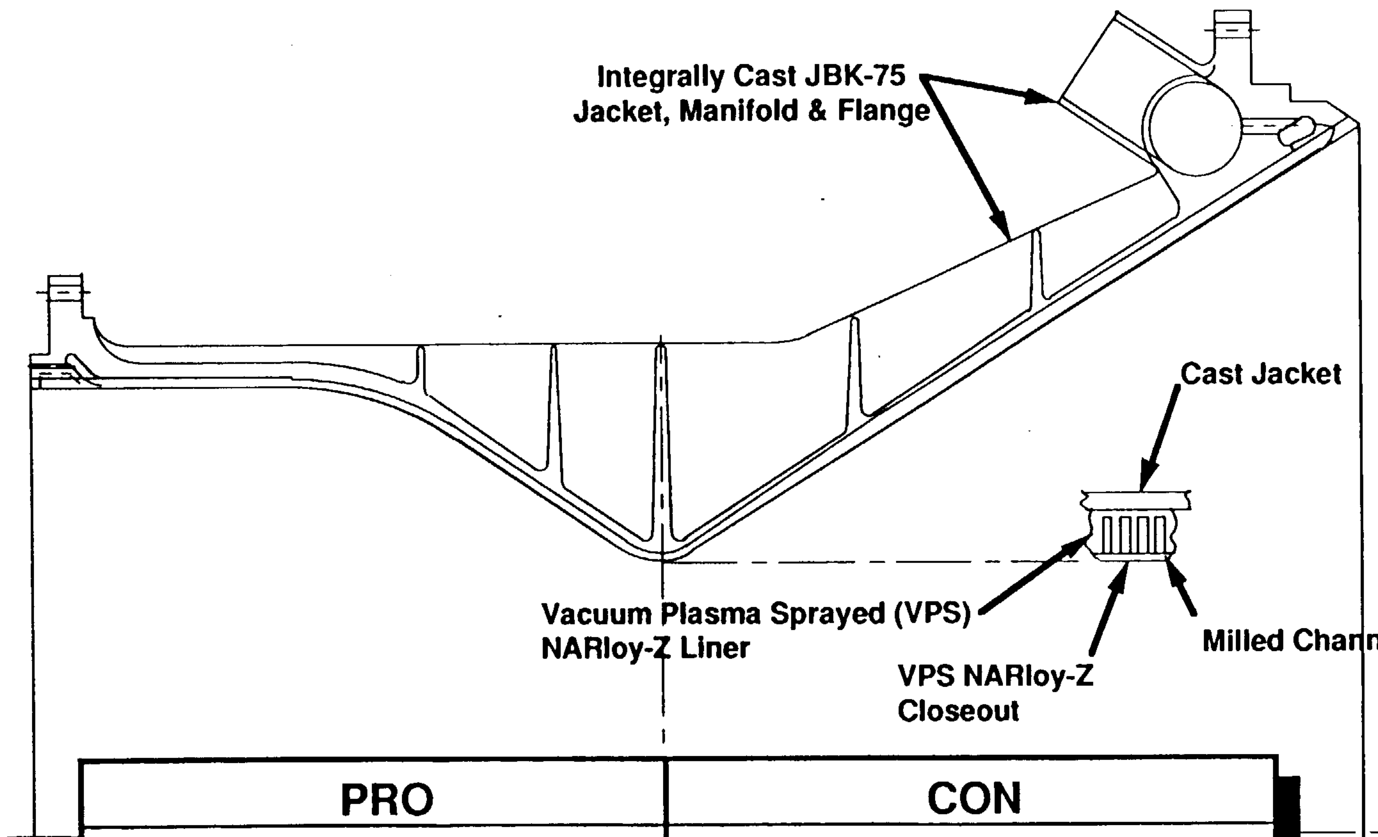
- **Cast jacket/VPS liner should be continued based on ultimate potential for cost and reliability benefits**
  - **Backup #1** - Brazed-in, tapered NARloy-Z tubes
    - Allows use of cast jacket
  - **Backup #2** - LIDB manifold with VPS closeout and structure
    - Retains use of wrought liner

LIDB COMBUSTION CHAMBER CONCEPT



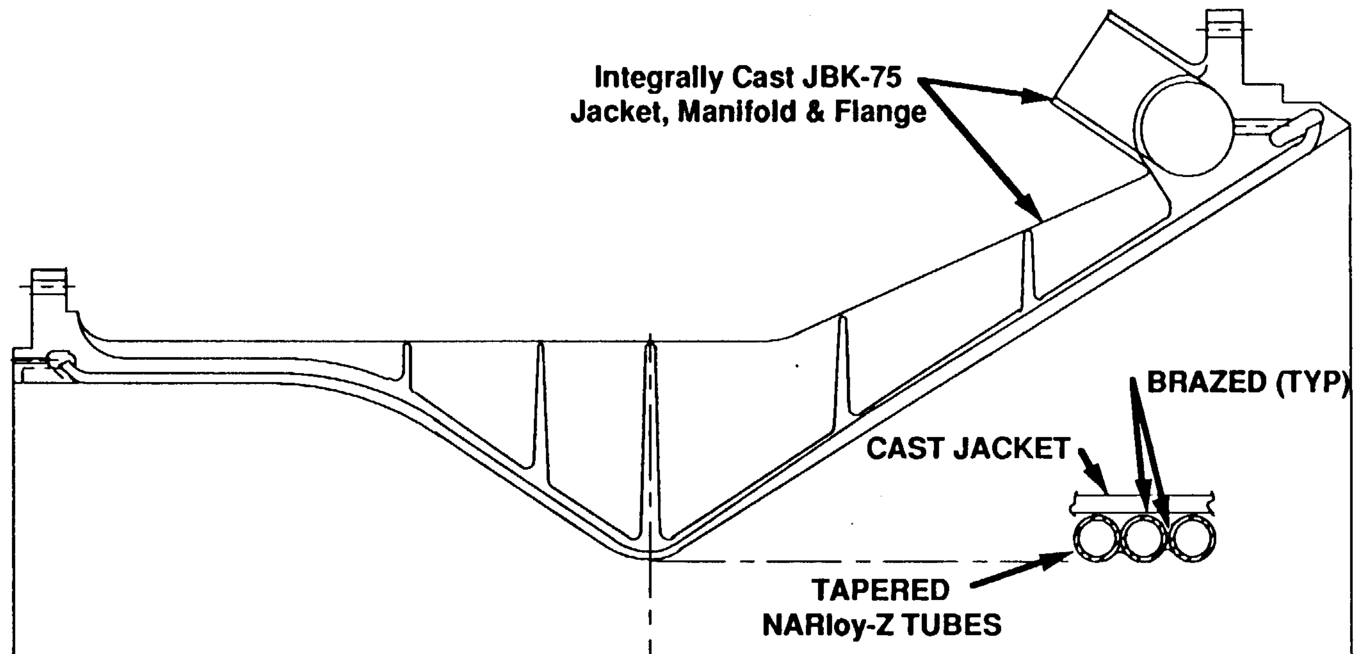
PRO	CON
• Retains use of wrought liner	• Low-mid cost
• Experience plating closeout	• Limited repair capability on braze joints

VPS LINER COMBUSTION CHAMBER CONCEPT



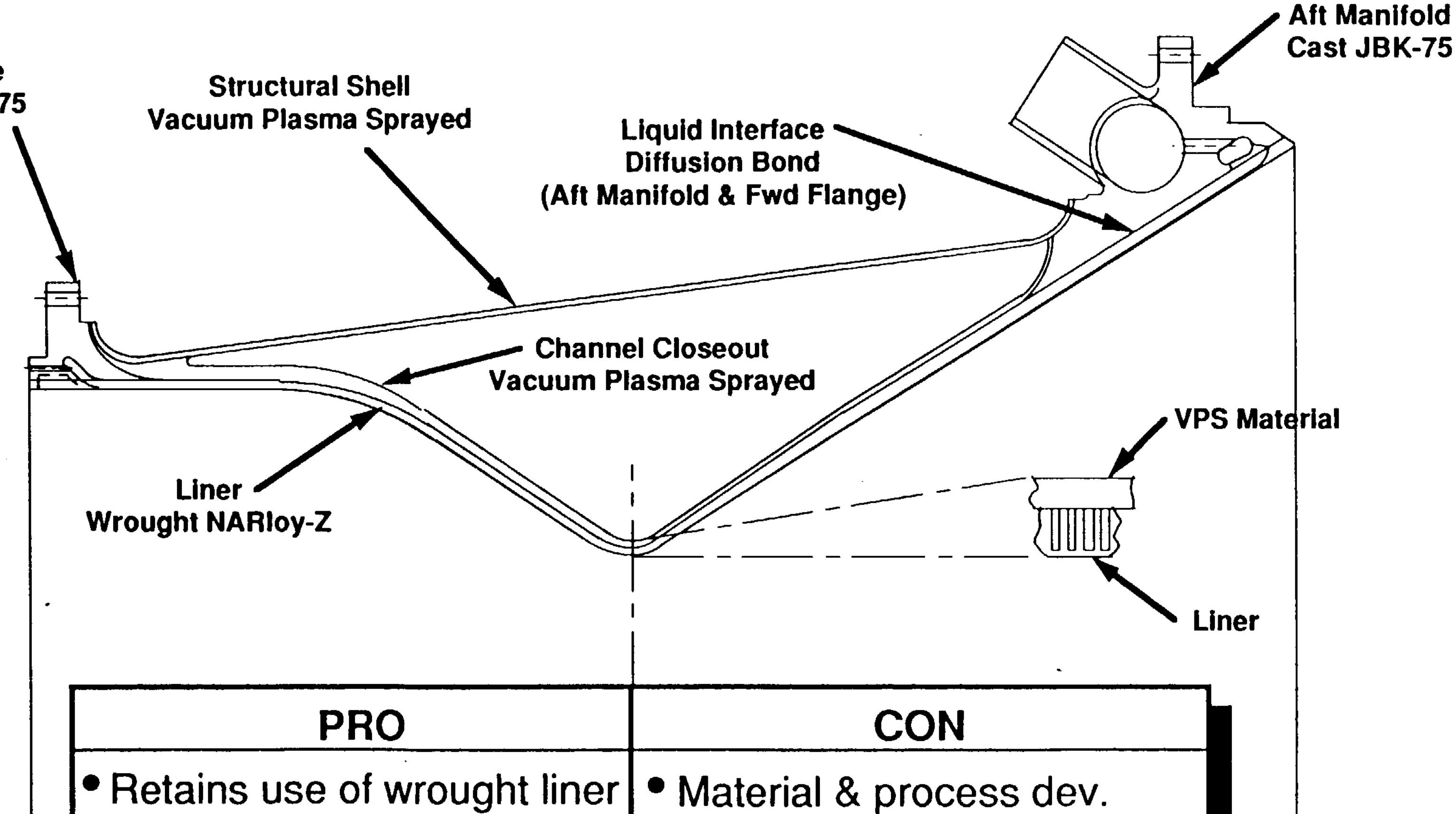
PRO	CON
• Lowest Cost • Highest Reliability	• Requires material and process development

CAST JACKET / NARloy-Z TUBE CONCEPT



PRO	CON
• Tubes / casting made in parallel	• Requires material and process development • Mid-high cost

VPS JACKET COMBUSTION CHAMBER CONCEPT

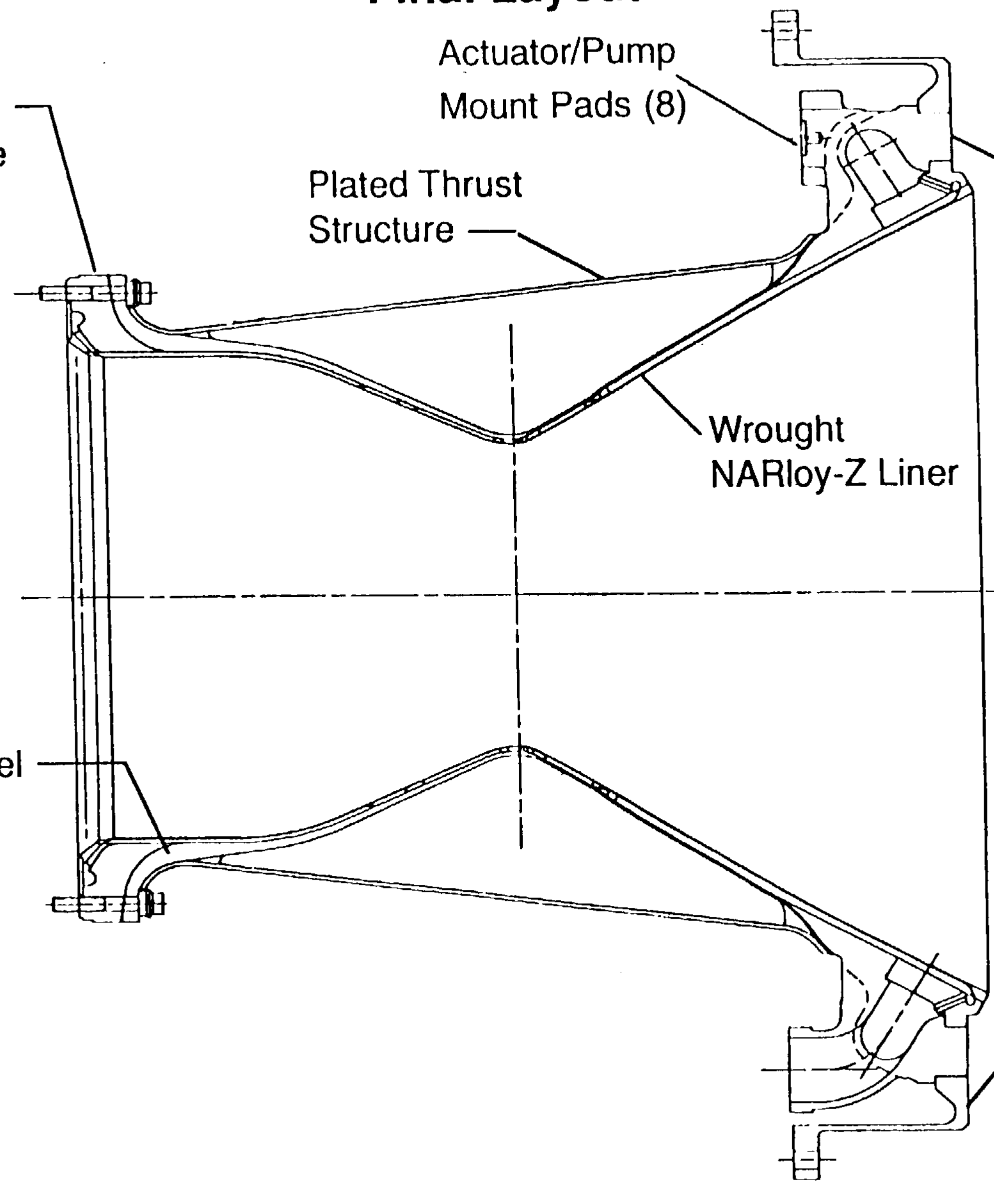


PRO	CON
• Retains use of wrought liner • Low cost	• Material & process dev. • Limited repair capability on braze joints

2.3.2 Design and Analysis

LIDB/EDNi Co COMBUSTION CHAMBER

Final Layout



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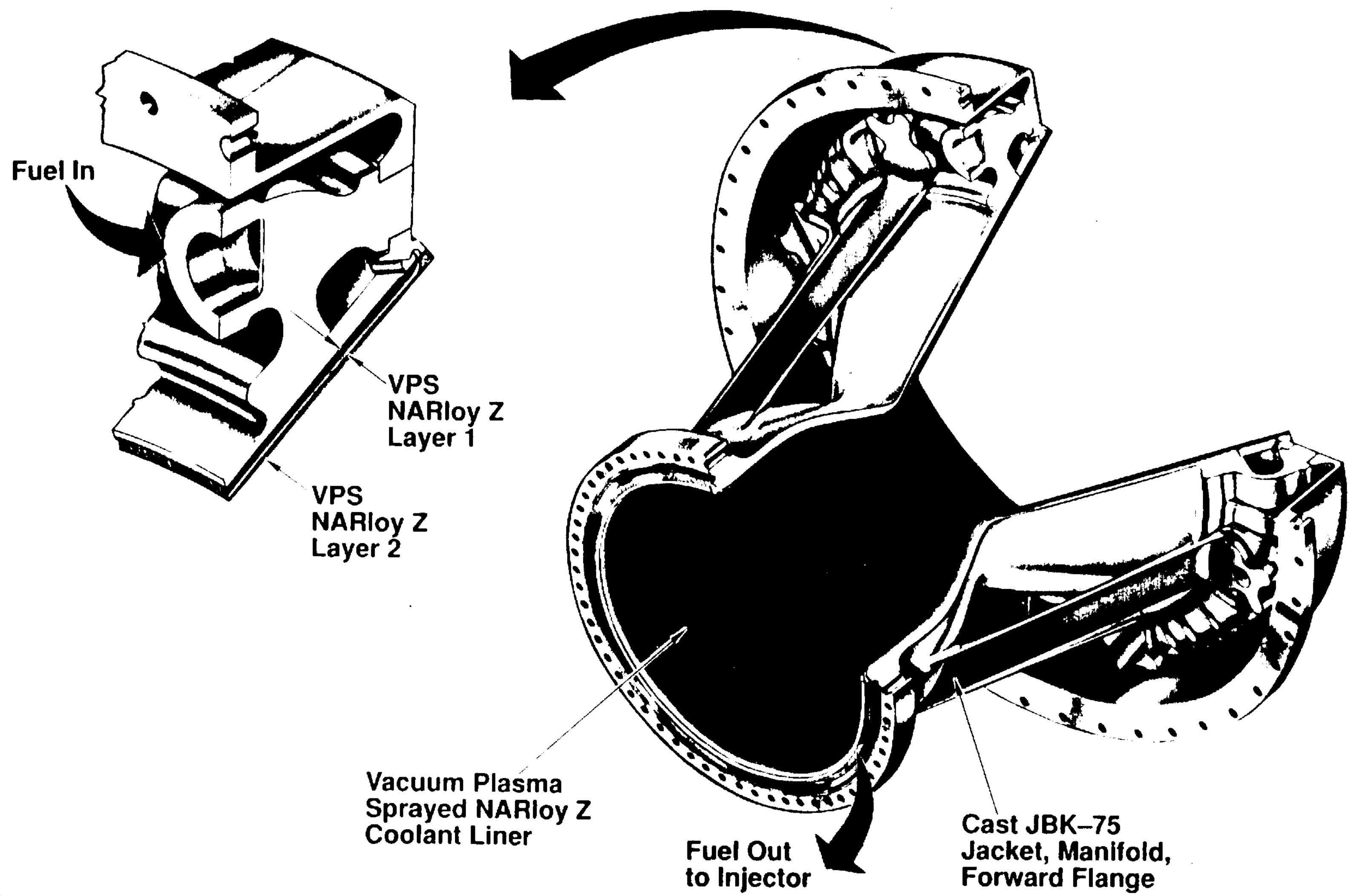
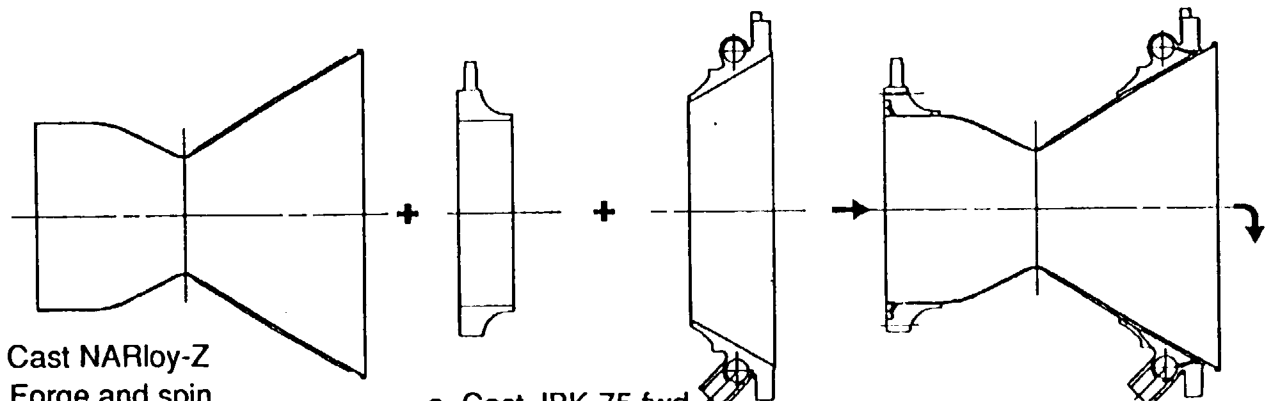
Combustion Chamber



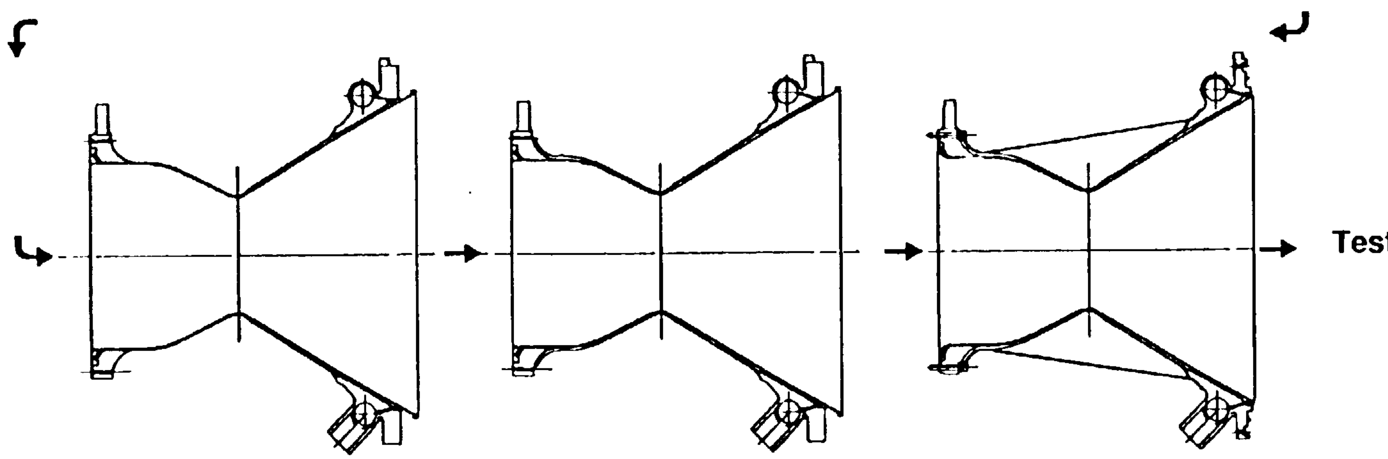
LIDB CHAMBER FAB FLOW



- Cast NARloy-Z
- Forge and spin
- Machine I.D. & O.D.
- Mill coolant channels

- Cast JBK-75 fwd flange & aft manifold
- Machine I.D.

- LIDB



- Machine flange & manifold
- Wax fill channels
- EDCu closeout channels

- EDNiCo plate jacket
- Machine jacket contour

- EDNiCo thrust cone
- Final machine interfaces

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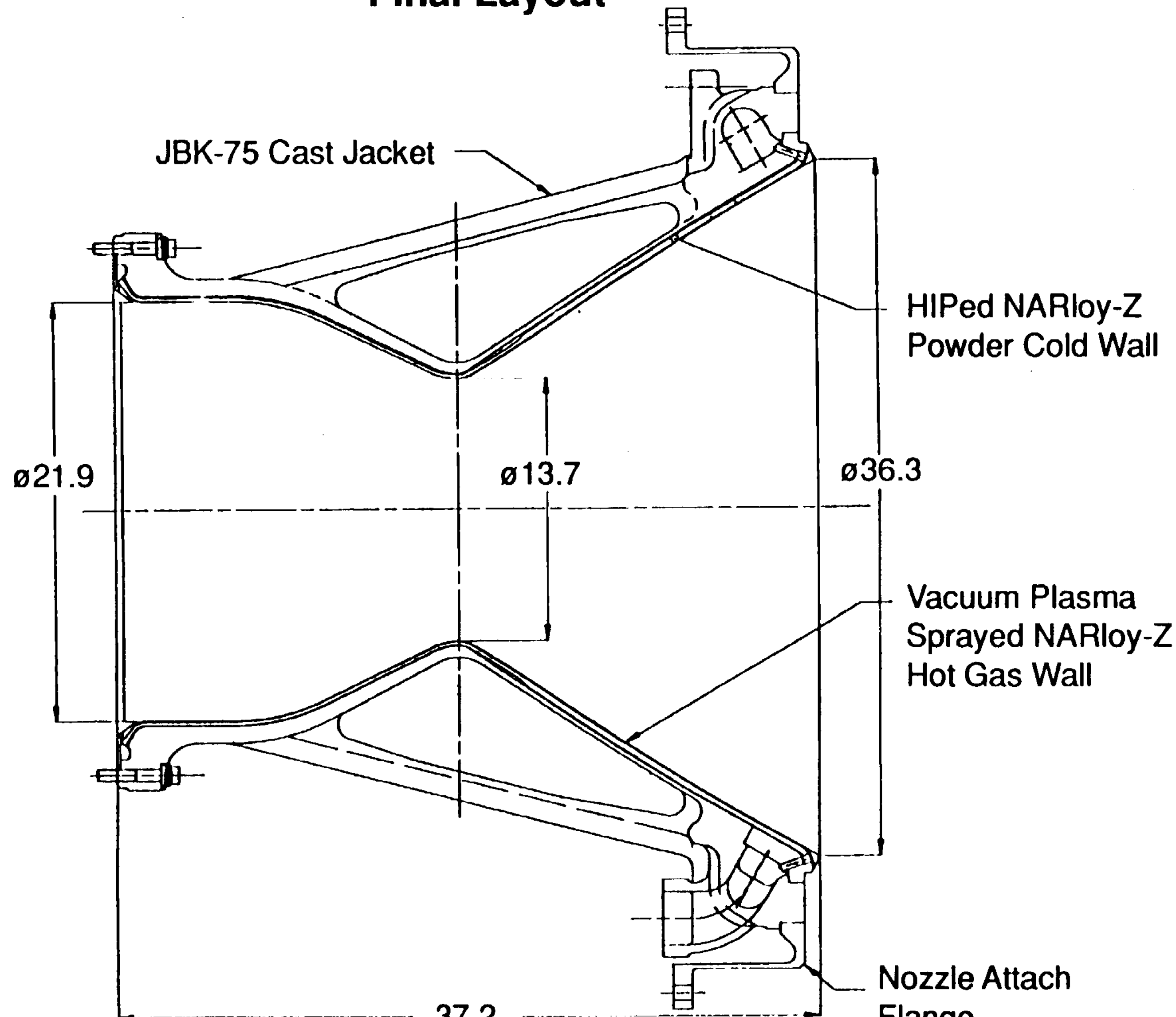
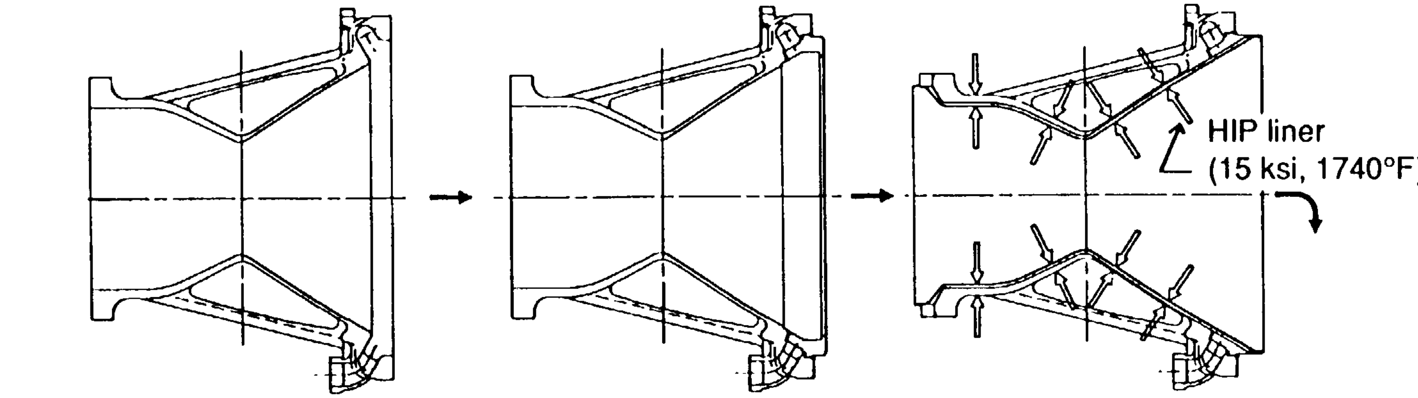
VPS COMBUSTION CHAMBER

Final Layout



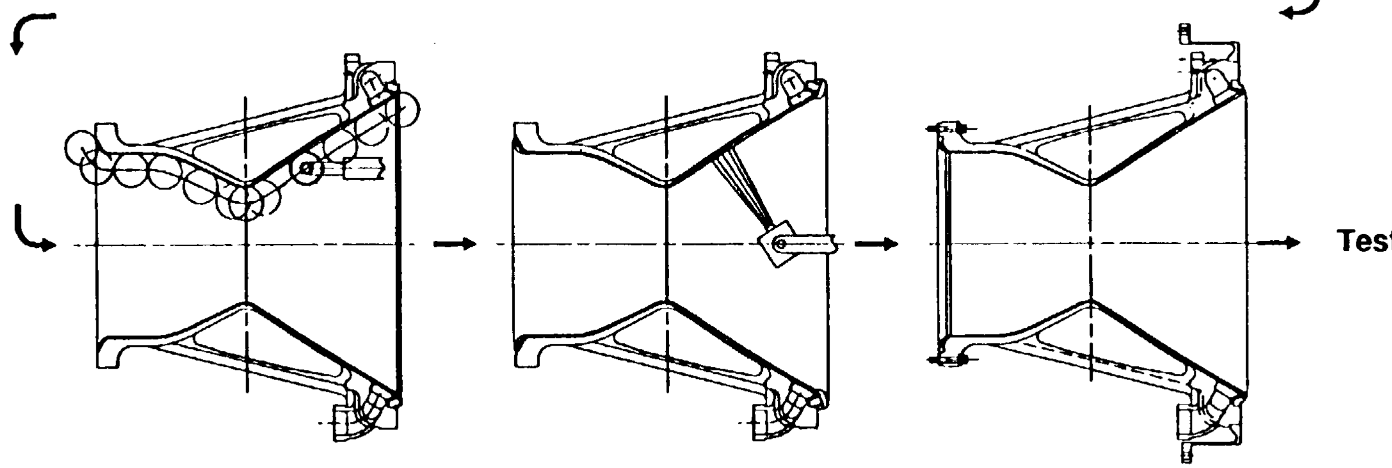
CAST JACKET/VPS LINER FAB FLOW



- Cast Jacket (JBK-75)

- Beam weld manifold closeout
- Machine I.D. contour

- HIP NARloy-Z powder to jacket I.D. (cold wall)
- Machine I.D. contour



- Mill coolant channels
- Drill feed holes & annulus

- Fill channels, vacuum plasma spray (VPS) NARloy-Z hot gas wall

- Beam weld nozzle flange
- Final machine interfaces

COMBUSTION CHAMBER DESIGN EVOLUTION

- **LIDB and VPS Designs**
  - Casting material changed from Inconel 625 to JBK-75
  - Aft manifold closeout changed from welded windows to a wrought material closeout ring on I.D.
  - Nozzle attachment flex ring added
  - Actuator/pump mount pads added

- **VPS Design**
  - Integral cast jacket thrust supports changed from "egg crate" ribs to braces

AFT MANIFOLD CLOSEOUT

- **11 closeout options were developed**
- **6 options screened out because of problems with:**
  - Fabrication robustness
    - Casting producibility
    - Joining method robustness
    - Inspection method producibility
  - Reliability
    - Inspection detectability and confidence
    - Operational concerns
- **Comparative evaluation conducted on remaining 5 options**

AFT MANIFOLD EVALUATION MATRIX

	Primary Determinants					Secondary Considerations					
Closeout Concept	Reliability	500th Unit Cost	Fabrication Robustness			ADP Total Cost	Development Risk			Compatibility Versatility	Weight
			(A)	(B)	(C)		(A)	(B)	(C)		
Welded Windows	4	$143,500 (3)	3	3	3	(1), (3)	3	3	4	4	5
O.D. TIG Welded	4	$166,800	4	3	4	(2)	4	4	3	5	5
O.D. Beam Welded	5	$172,800	4	5	5	(2)	5	4	2	5	5
Bolted	1	$183,400	4	4	3	(2)	4	5	5	4	4
I.D. Beam Welded	5	$179,155	5	5	5	(2)	5	4	4	5	5

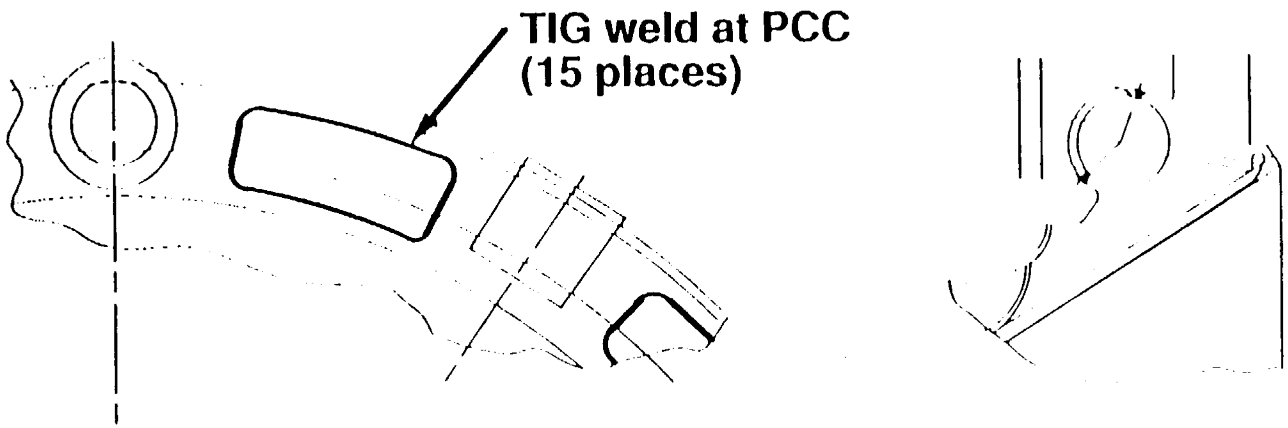
Legend: 5 = Best. Other ratings proportional to percent worse

NOTES:

Robustness
(A) = Casting and risk
(B) = Machining and welding
(C) = Inspection

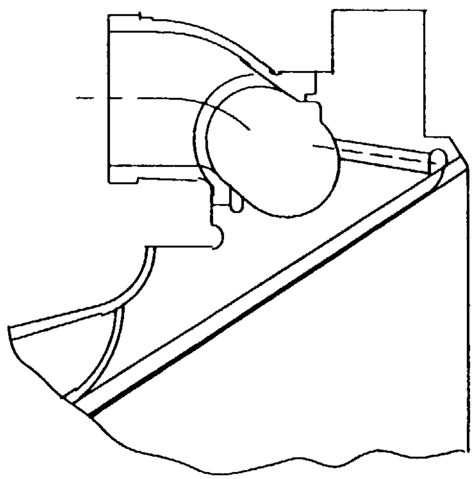
Cost
(1) - PCC estimates 10 - 20 castings could be needed to yield one for hot-fire
(2) - PCC estimates 6 - 10 castings could be needed to yield one for hot-fire
(3) - PCC quote based on a .210 thick weld window

AFT MANIFOLD
WELDED WINDOW CONCEPT

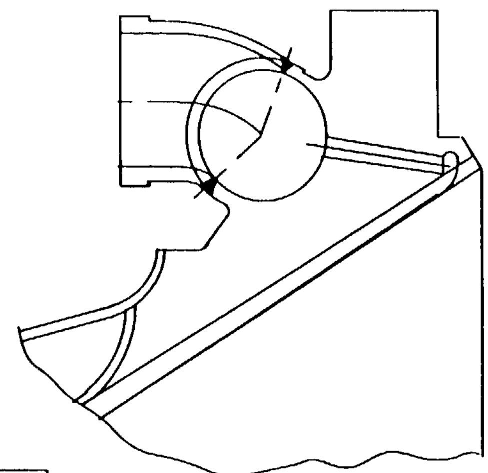


Windows allow core support and access to I.D. for inspection / repair

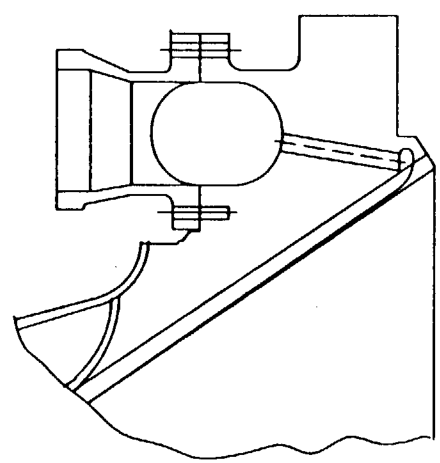
AFT MANIFOLD
2-PIECE CASTING CONCEPTS



O.D. beam welded



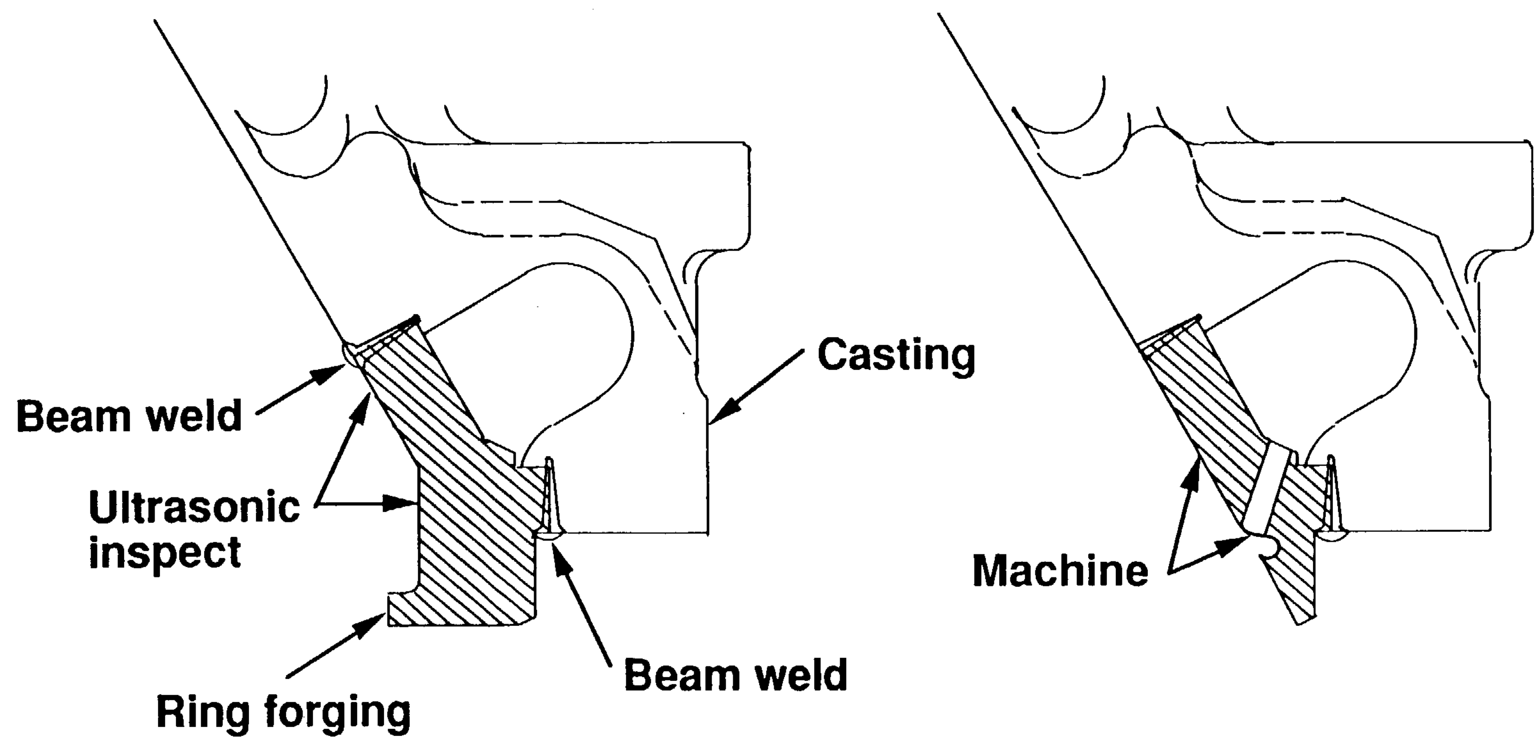
O.D. T.I.G. welded



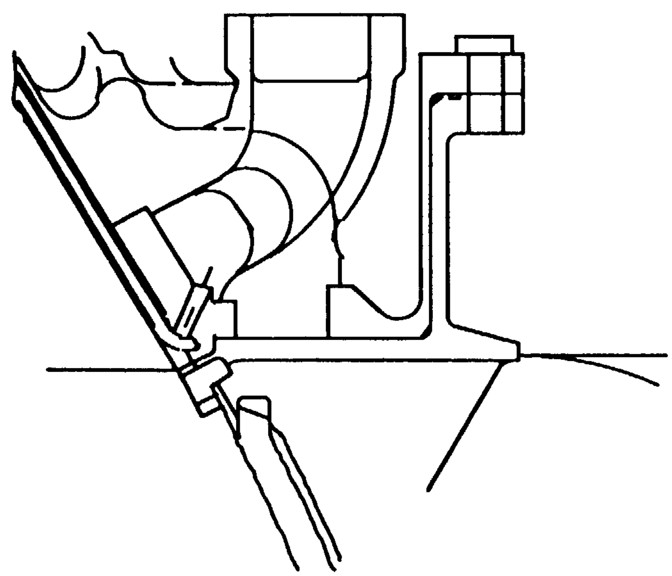
Bolted

I.D. WELD CLOSEOUT SELECTED

- Eliminates inspection development risk
- Equally applicable to both LIDB and VPS chambers

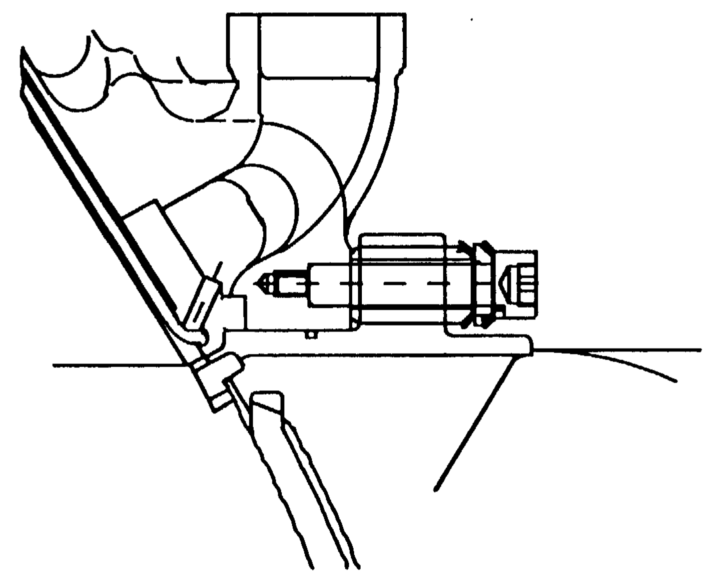


FLEX RING SELECTED FOR COMBUSTOR/NOZZLE ATTACHMENT



Flex Ring

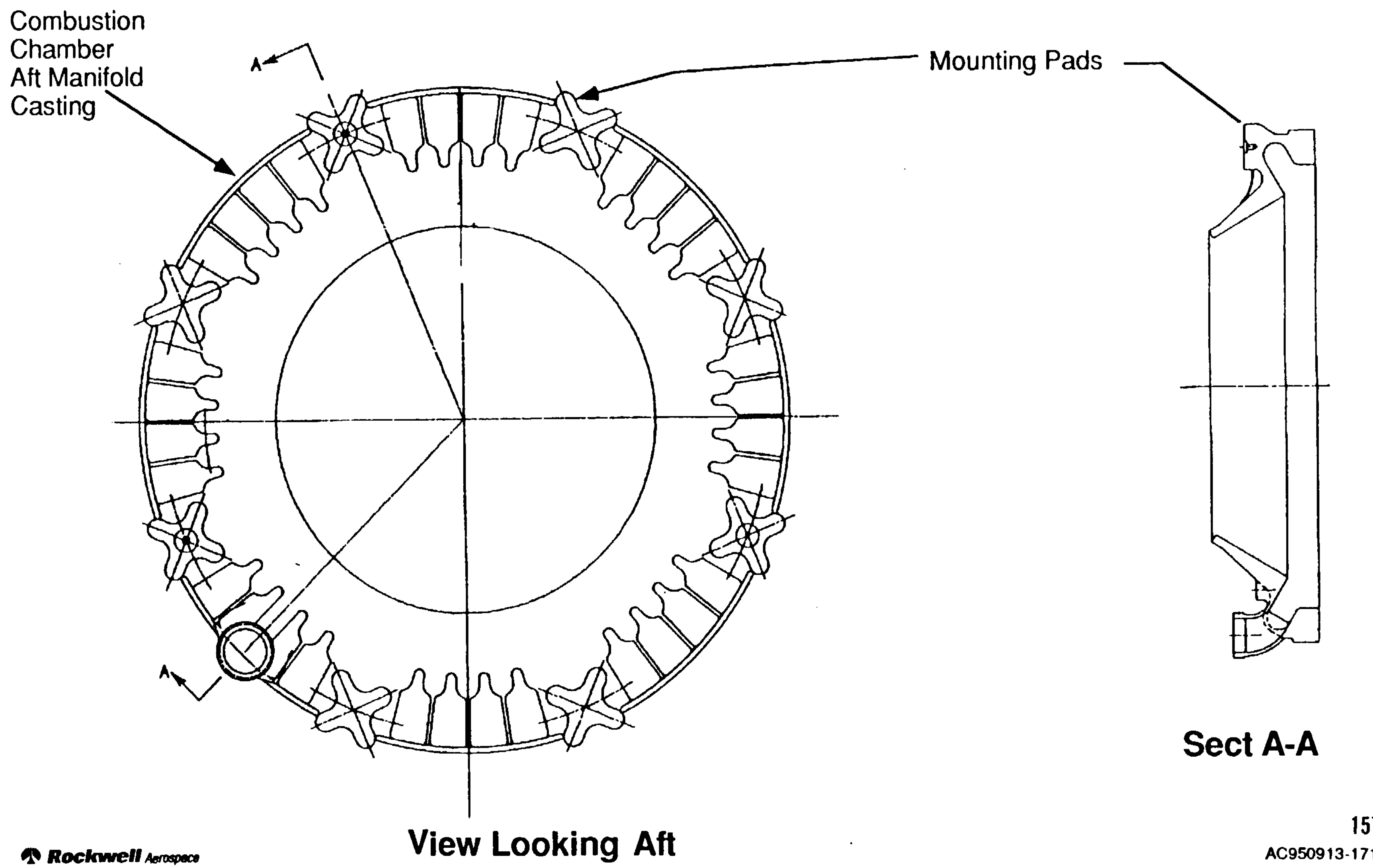
- **Simply bolted connection - nozzle and combustor flange same temperature**
  - Flow in interface an issue
- **Relative thermal movement of insider contour**
  - Axial: 0.020" separation
  - Radial: 0.117" shift



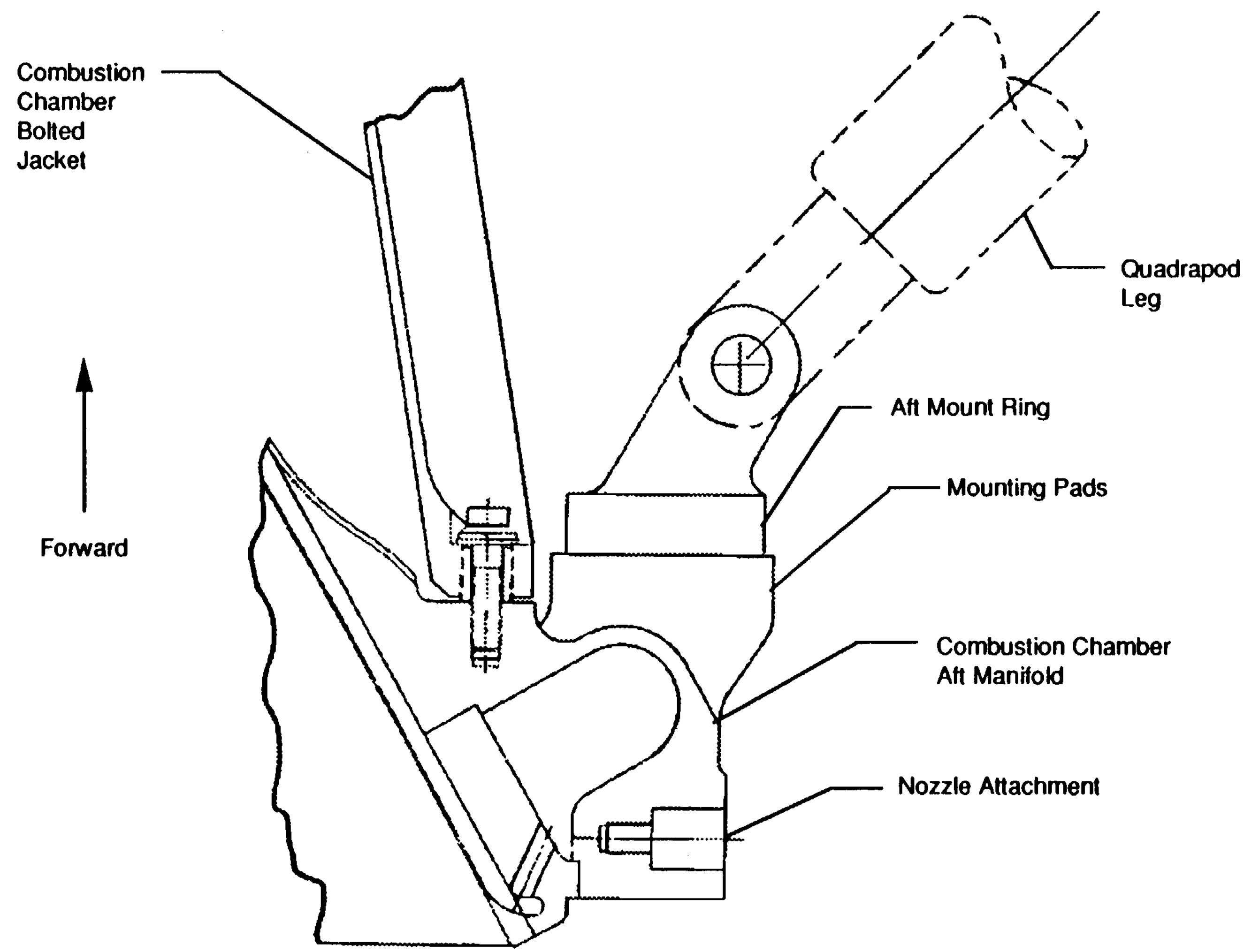
Radial Pins

- **Sleeves allow for thermal growth**
  - Potential binding of sleeves
  - Seal must accommodate expansion, sliding
- **Relative thermal movement of insider contour**
  - Axial: 0.012" separation
  - Radial: 0.118" shift

COMBUSTION CHAMBER ACTUATOR/PUMP MOUNT PADS



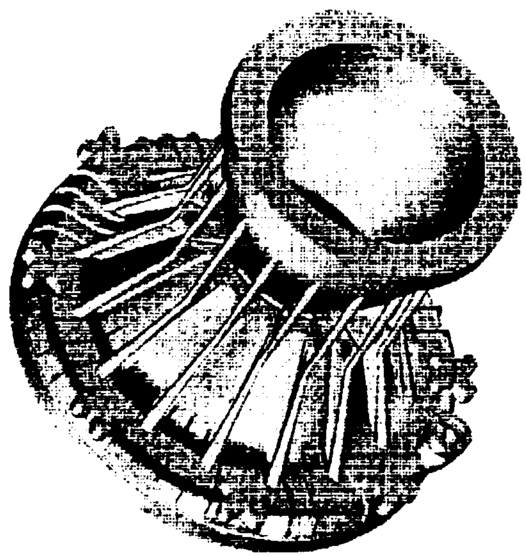
COMBUSTION CHAMBER ACTUATOR/PUMP MOUNT PAD ATTACHMENT



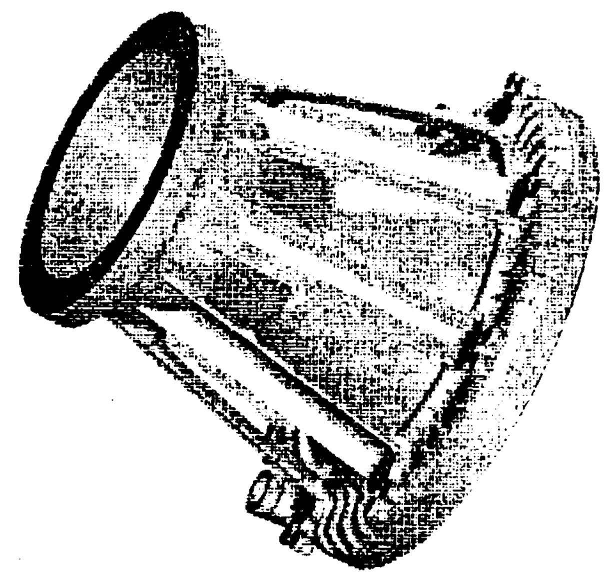
CAST JACKET CONCEPT SELECTION

- **Two cast jacket concepts were developed**
  - 16 rib design evolved from "egg crate" concept
  - 8 brace design evolved from "double wall" concept
- **Both designs meet structural requirements**
- **Weights nearly equal**
- **Selection responsibility delegated to PCC**

CAST MANIFOLD AND JACKET DESIGN OPTIONS



16 Rib Design



8 Brace Design

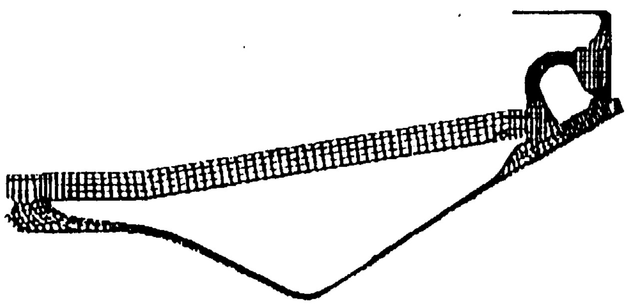
- Both were acceptable casting designs

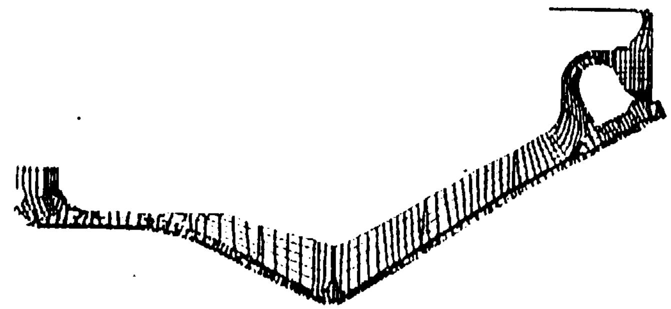
JACKET CASTING DESIGN COMPARISON

	Eight Braces	Sixteen Ribs
Tooling	+ Fewer wax components.	- More complex tooling and assembly.
Dimensions	- Possible buckling of braces - Wall thickness variability	+ Less wall thickness variation. + PCC P/N 9595 dimensional experience.
Gating	+ Good tapers/transitions. + Thinner shell - faster cooling.	+ Better tapers. + PCC P/N 9595 experience applicable. + Shape better for directional solidification
Shell	- Builds slower - cost, stability +/- Flexible - less tearing/ more distortion.	+/- Builds fast- less distortion/slower cooling +/- Stiffer - less bulging/more cracking
Handling	- Possible brace distortion/breakage.	+ More stable wax assembly.
Welding	+ Less corners/easier access. + Less transitions - easier to make quality welds	+ Access is good. - More difficult transitions to weld.
Inspection	+ Easier to x-ray and FPI. + More areas covered accurately.	- More junctions that have low sensitivity. - Requires more film/shots. - More surfaces for FPI indications.

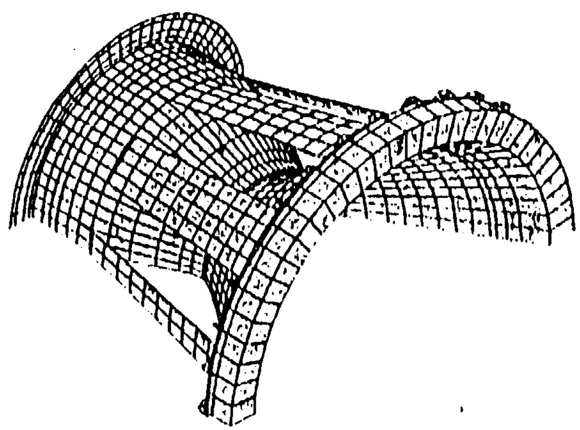
The eight brace design was judged superior

COMBUSTION CHAMBER FINITE ELEMENT MODELS

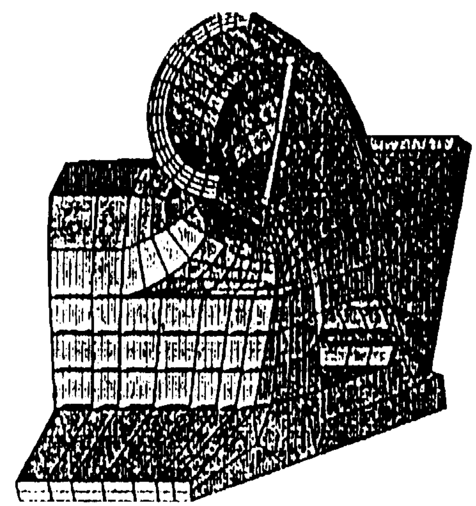




AXISYMMETRIC MODELS



3-D CAST JACKET MODEL

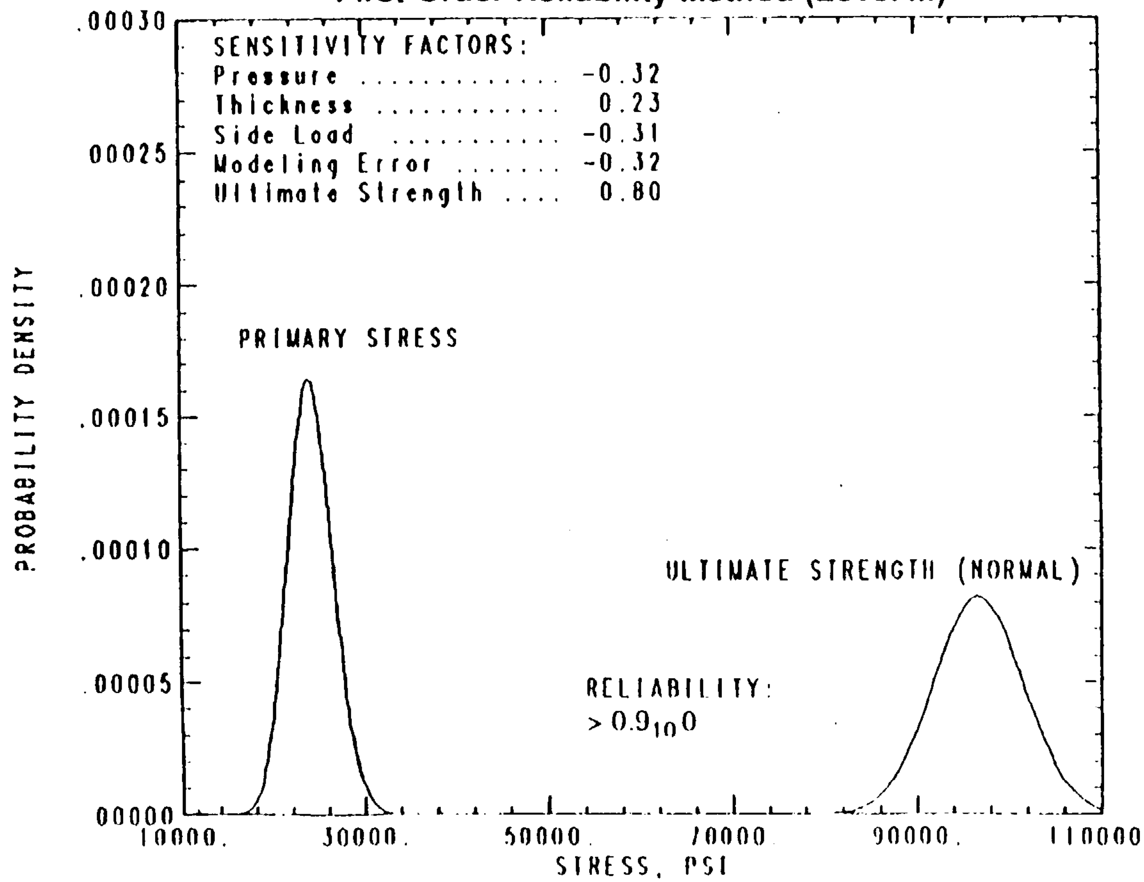


3-D COOLANT INLET MODEL

PROBABILITY DENSITY FUNCTIONS FOR PRIMARY STRESS

Main Combustion Chamber AFT Manifold Casting

Failure Mode: Primary Stress
First-Order Reliability Method (Level III)



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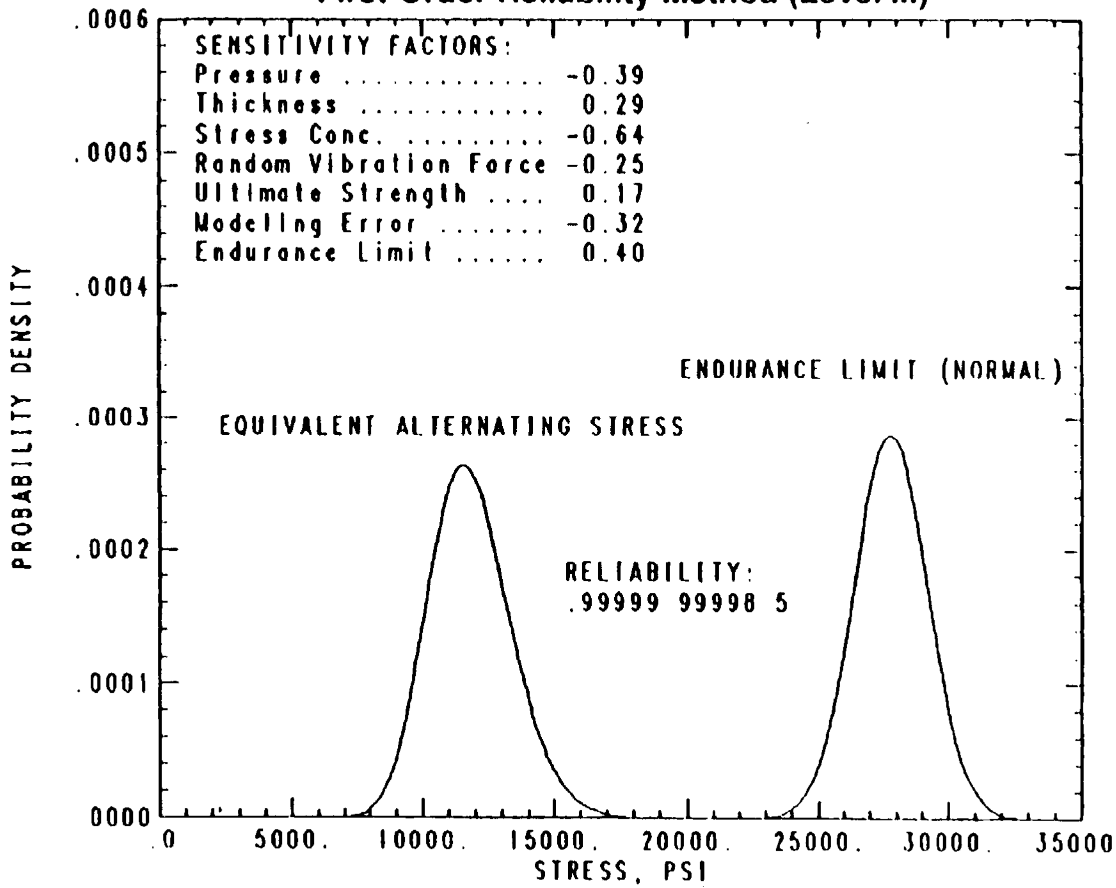
90ALS 072 182

PROBABILITY DENSITY FUNCTIONS FOR HIGH CYCLE FATIGUE

Main Combustion Chamber AFT Manifold Casting

Failure Mode: High-Cycle Fatigue
First-Order Reliability Method (Level III)



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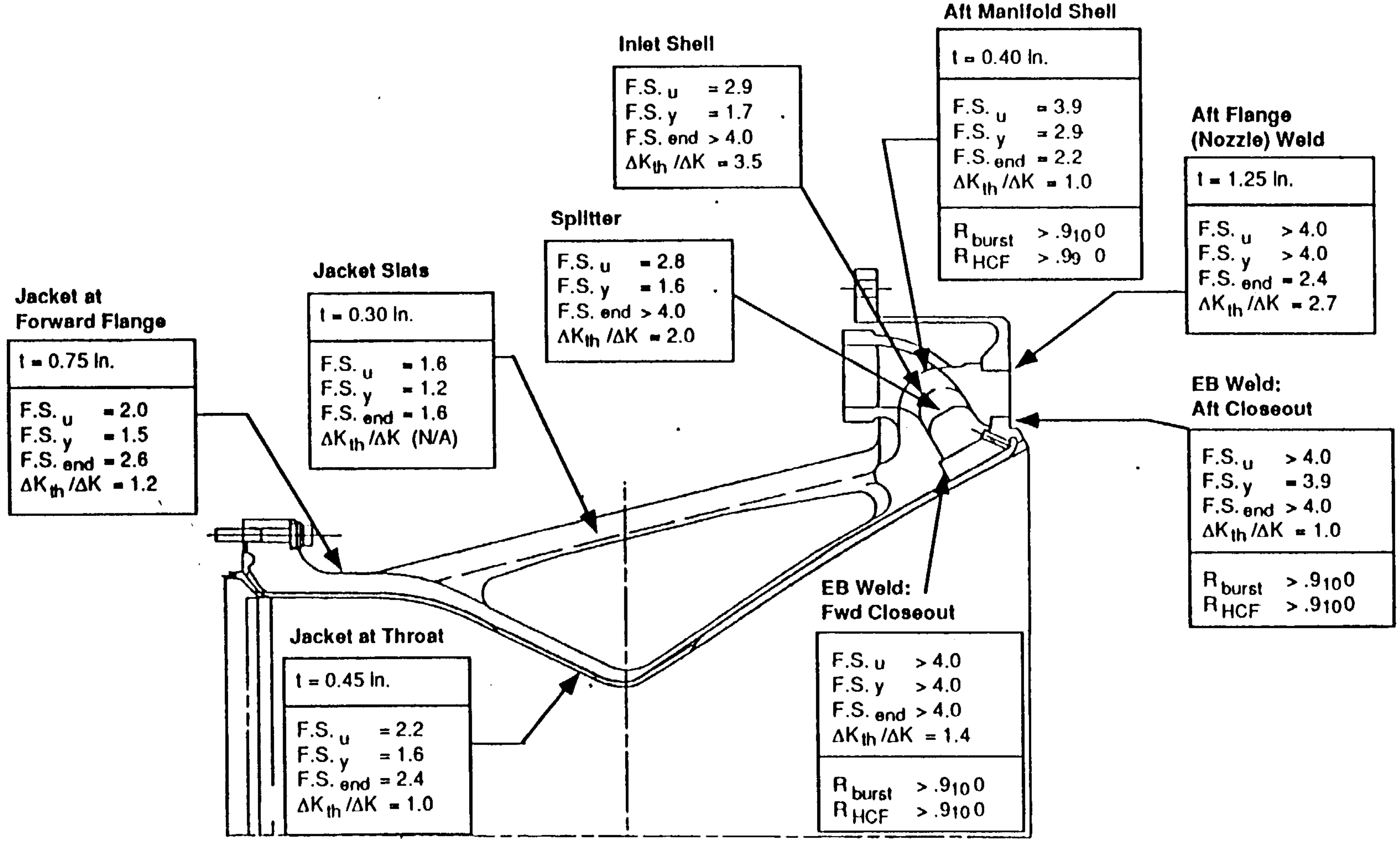
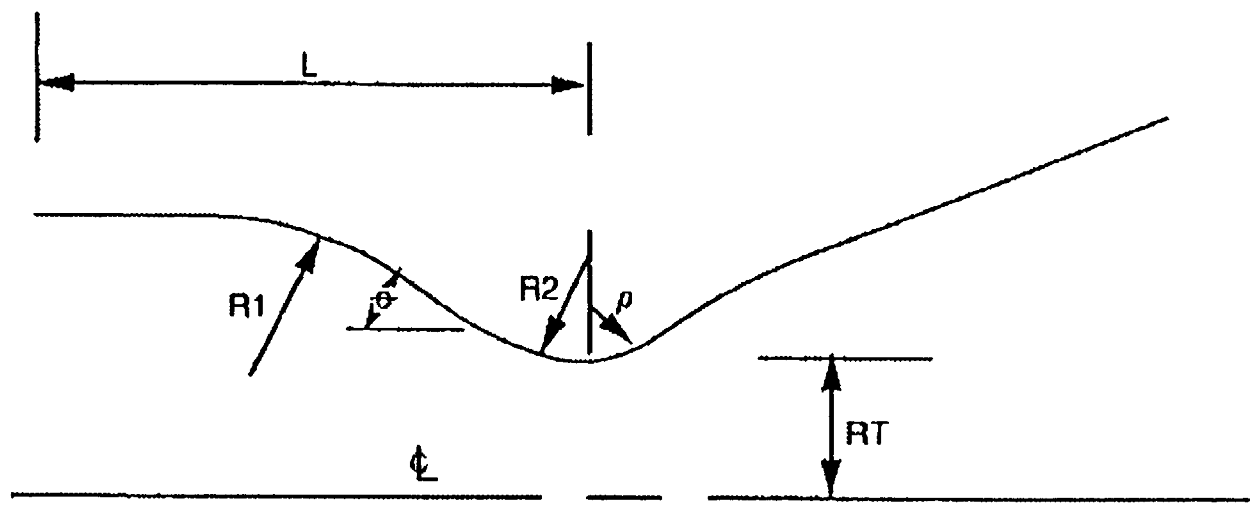
COMBUSTION CHAMBER SAFETY AND RELIABILITY SUMMARY



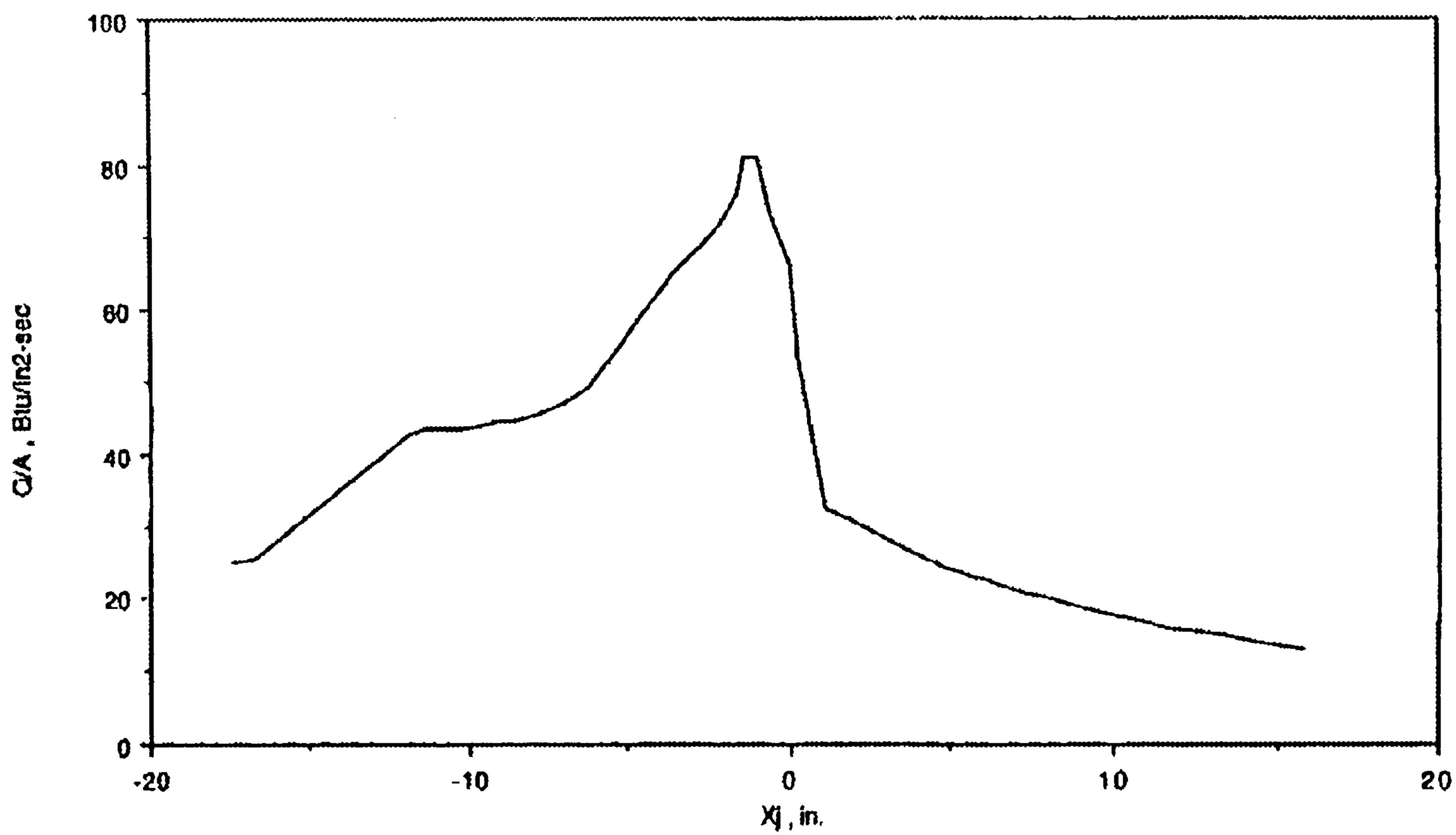
Combustion Chamber Reliability Allocation = 0.99992

AEROTHERMAL ANALYSIS
Combustion Chamber Contour
December 1989



L	17.45
R1/RT	1.63
R2/RT	0.494
ρ/Rt	0.2
RT	6.461
CR (Contraction Ratio)	2.641
Ø	25.42
L/RT	2.70

COMBUSTION CHAMBER
WALL HEAT FLUX PROFILE



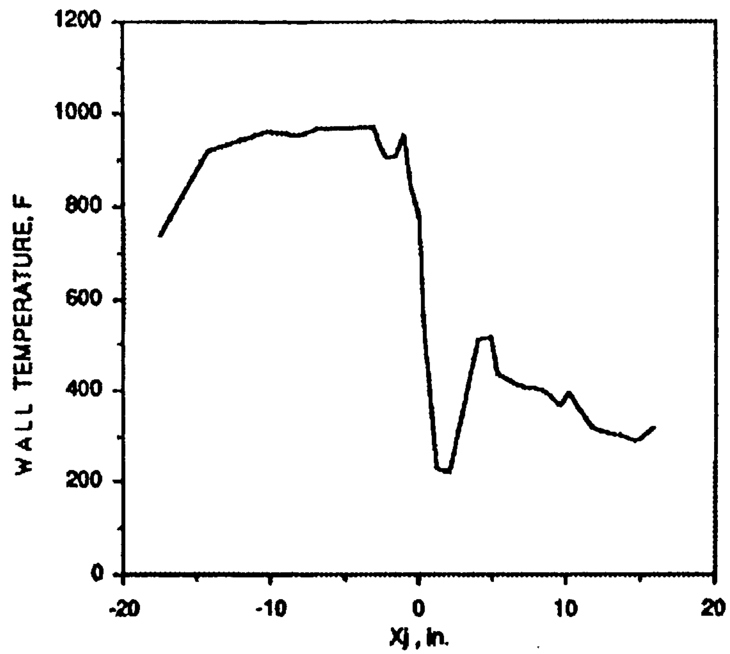
COOLING CHANNEL DESIGN CONSTRAINTS

- Coolant mach number ≤ 0.3
- Coolant bulk temperature rise (°F) ≤ 500
- Land width/channel width ratio ≥ 1.0
- Hot gas wall temperature (°F) ≤ 980
- Minimum cycle life ≥ 60

COOLING CHANNEL GEOMETRICAL CONFIGURATIONS

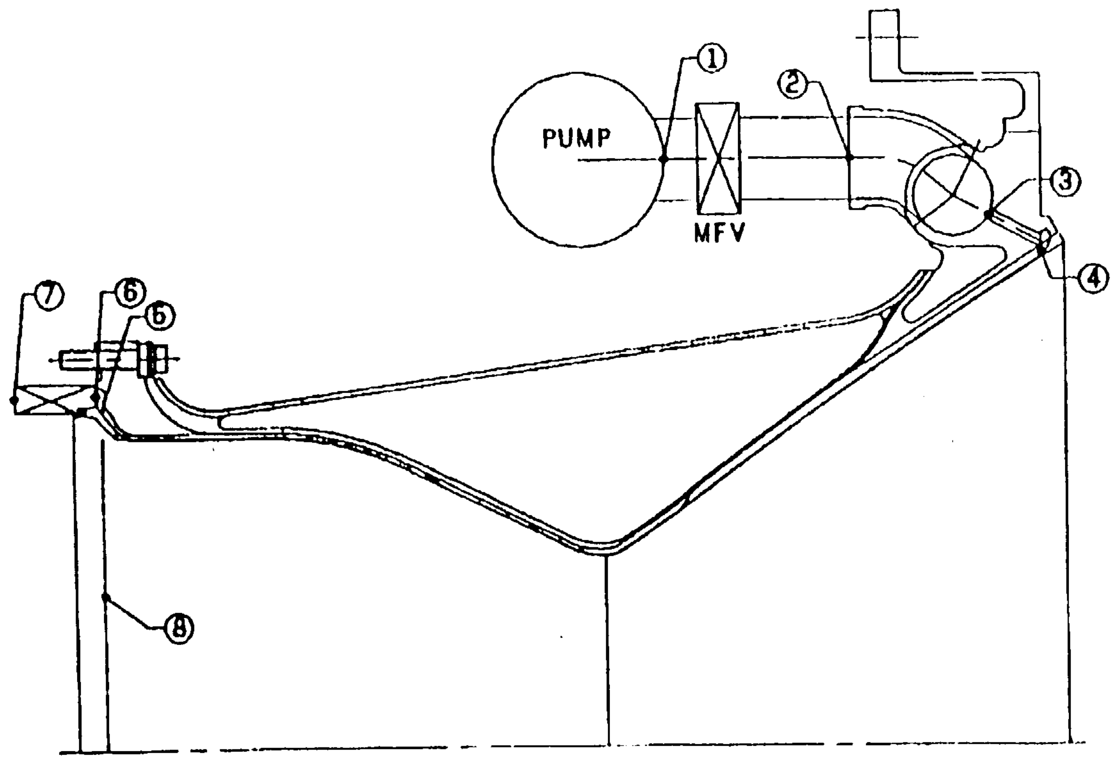
• Injector/throat length (in)	17.45
• Chamber contraction area ratio	2.64
• Number of channels	540
• Minimum channel width (in)	0.037
• Minimum wall thickness (in)	0.024
• Minimum land width (in)	0.0385

BASELINE COMBUSTION CHAMBER THERMAL PERFORMANCE SUMMARY



Aft End Temperature (F)	320
Throat Temperature (F)	950
Forward End Temperature (F)	785
Maximum Wall Temperature (F)	974
ΔP (psi)	1089
ΣQ (Btu/sec)	76130
ΔTB (R)	488

THRUST CHAMBER DELTA-P LOSSES



Distribution

1-2	Inlet Delta ΔP	159 psi
2-3	Inlet Manifold ΔP	24 psi
3-4	Entrance to Chan. ΔP	16 psi
4-5	Channel ΔP	1089 psi
5-6	Exit ΔP/Manif. Losses	58 psi
6-7	Mixer ΔP	104 psi*
7-8	Injector ΔP	295 psi
	Total	1745 psi
	Inj. End Stag Press	2320 psi
	Pump Press	4065 psi

* Note: Zero pressure recovery assumed.
May recover 150 psi

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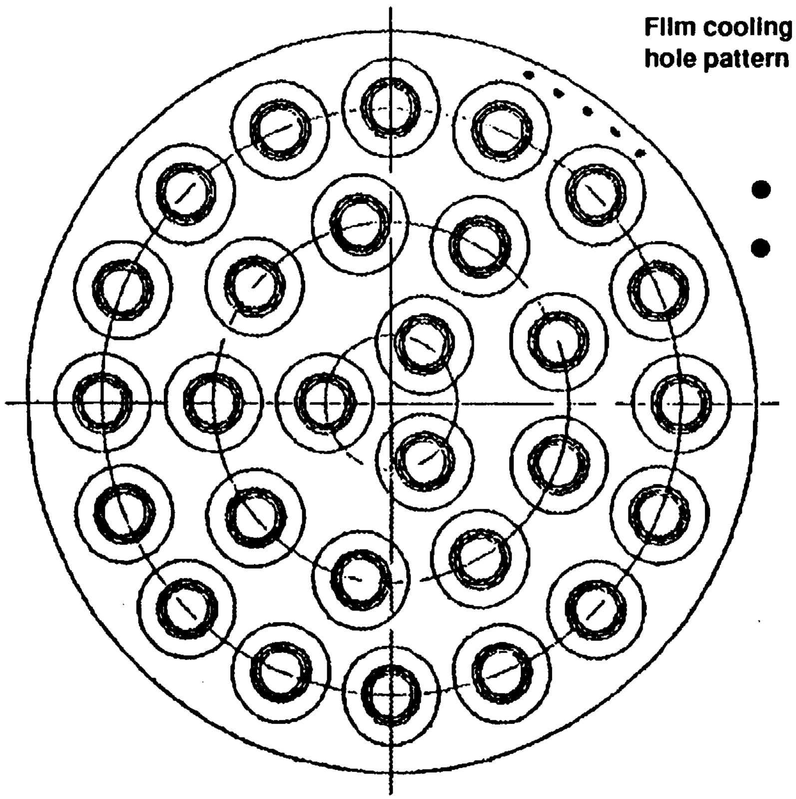
INJECTOR/COMBUSTION CHAMBER COMPATIBILITY
MR BIASING/FILM COOLING



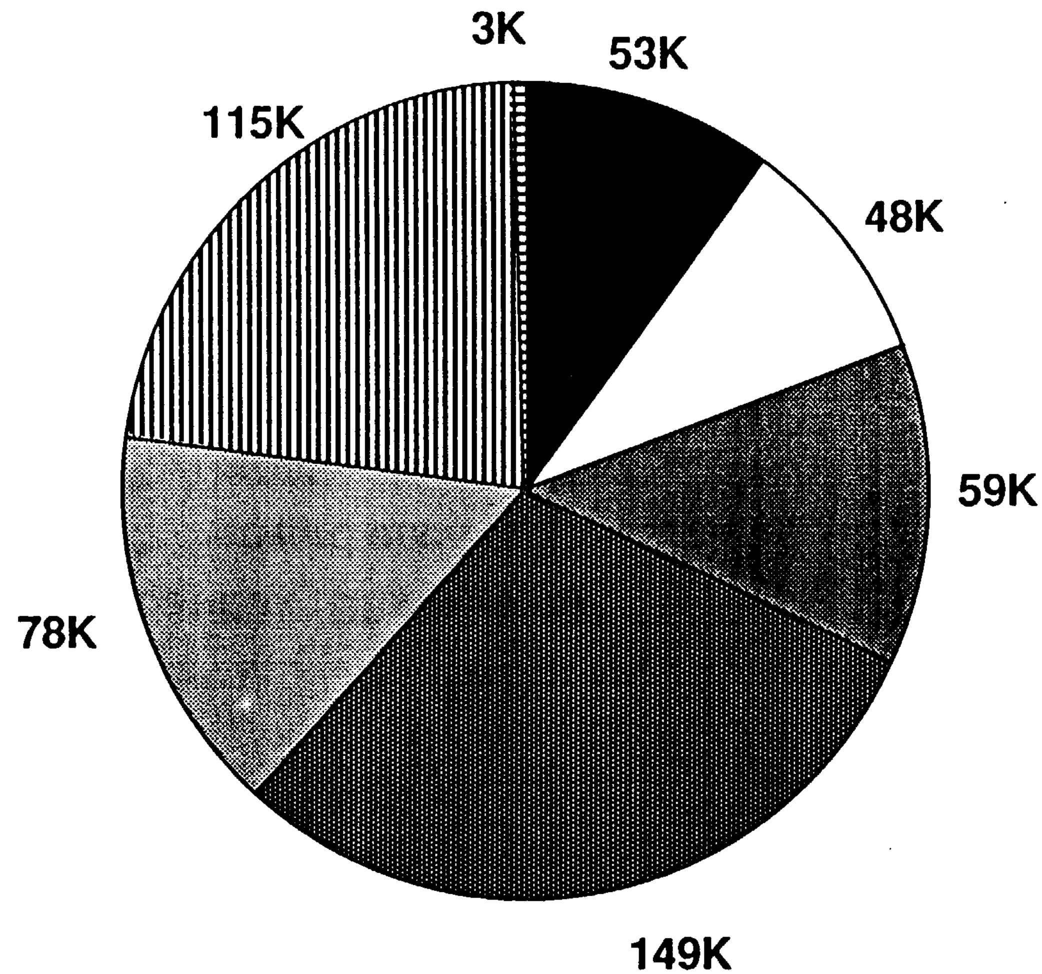
40 - Class Injector

- **Outer row biasing MR** 6.0
- **Number of outer row elements** 74
    - Number of film coolant holes 296
    - Hole diameter 0.04
    - Film coolant flowrate 6 #/sec

INJECTOR/COMBUSTION CHAMBER THERMAL PERFORMANCE COMPARISON

	Baseline	MR biased/ Film Cooled
• **Heat flux (Btu/in^2-sec)**		
• Forward end	24	19.7
• Throat	66	53
• AFT end	11.7	10.8
• **ΔP (psia)**	**1089**	**650**
• **ΣQ (Btu/sec)**	**76130**	**51300**

LIDB COST BREAKDOWN
September 1991



500th Unit cost at rate of 30/yr, 1991 $

Direct Costs
- Spun Liner
- Manifold Casting
- Other Mat'l
- Mfg Labor

Support Costs
- % of Fab Labor
- Level of Effort Labor
- Misc

Note: Excludes G&A, COM, Fee

Total = $505,000

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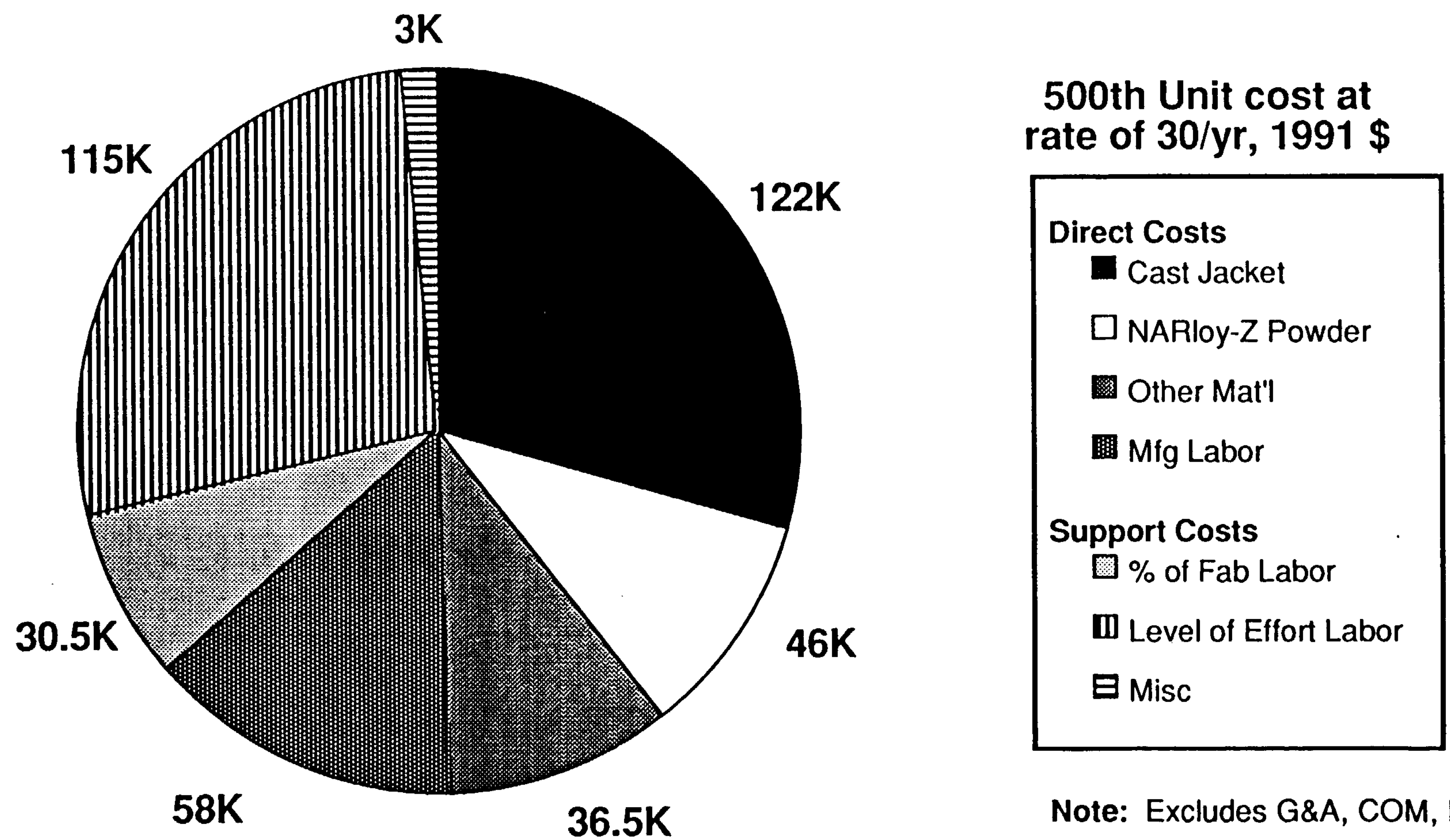
VPS COMBUSTION CHAMBER COST BREAKDOWN
September 1991



Note: Excludes G&A, COM, Fee

Total = $411,000

2.3.3 JBK-75 Structural Castings

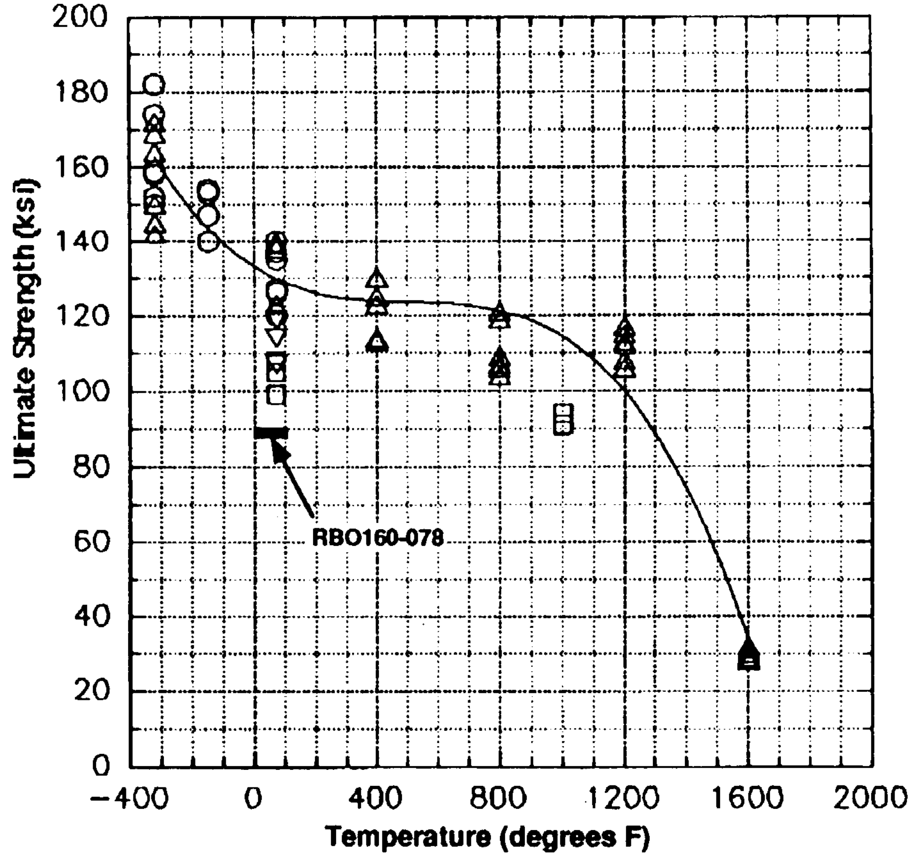
CANDIDATE ALLOY COMPARISON

Casting Material Criteria	JBK-75	Incoloy 909	INCO 718	INCO 625
HEE Resistance	Good	Good	Poor	Adequate
Corrosion Resistance	Good	Poor	Excellent	Excellent
Yield strength - Ductility (KSI) (%El)	85 10	120 8	125 5	40 20
Weldability	Excellent	Good	Good	Excellent
Castability	Excellent	Adequate	Excellent	Very Good
Density - lbs/in^3	.286	.296	.297	.305
Material Class	Fe Base	Fe Base + Cb +Co	Ni Base + Fe + Cb	Ni Base + Cb + Mo
Coefficient of Thermal Expansion (RT-1400°F) NARloy-Z=10.4	10.3	5.6	8.9	8.8

Selected

CAST JBK-75 ULTIMATE STRENGTH

STA Condition, Air Environment

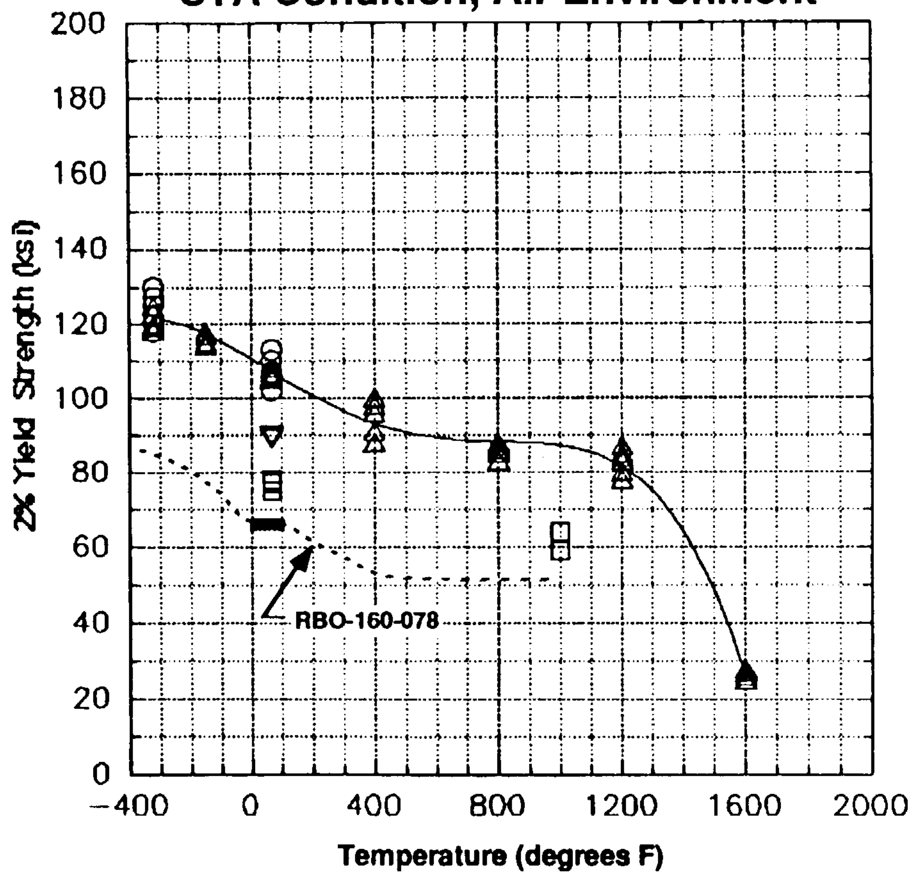


Δ or ○ 1/4" dia. Cast to Size ∇ 1/4"T Cast Plate □ 1/2"T Cast

94LS/077-004

CAST JBK-75 YIELD STRENGTH

STA Condition, Air Environment



Δ or ○ 1/4" dia. Cast to Size ∇ 1/4"T Cast Plate □ 1/2"T Cast Plate

94LS/077-005

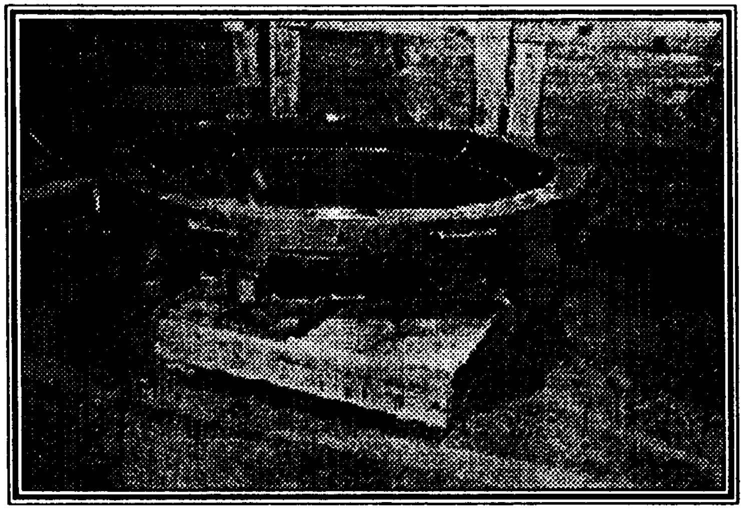
CAST JBK-75 MATERIAL PROCESS ACCOMPLISHMENTS

- **Issued casting specification RB0-160-078**
- **Determined casting parameters**
  - Mold preheat cycle and temperature
  - Metal pour temperature
  - Filter size
- **Determined HIP cycle**
- **Castability and weldability test specimens showed excellent results**
- **Determined Revert recycle limits**

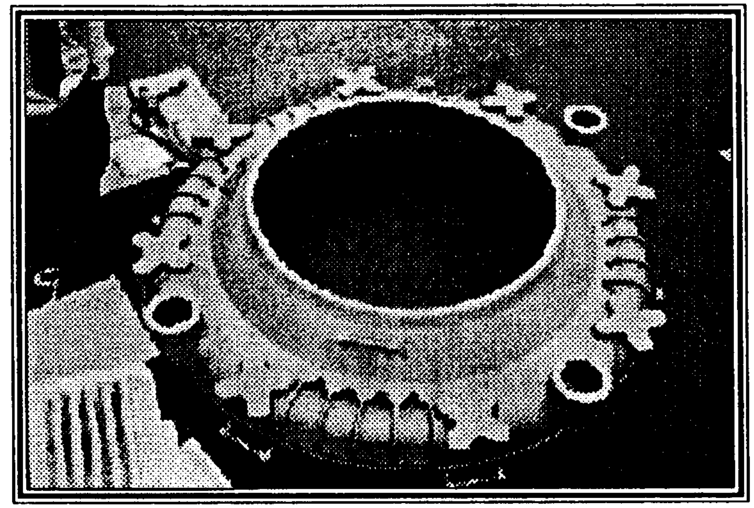
JBK-75 CASTINGS PRODUCED

- **Eccentric Rings**
- **Hot Tear Spider**
- **Weldability Hockey Puck**
- **Test Plates - HIP, Fracture Mechanics, Surface Characterization**
- **Large Structural Casting - April 1990**
- **Cast Throat - Sept. 1990**
    - Combustion Chamber Aft Manifold - Mockup - February 1991
    - Combustion Chamber Integral Jacket - Mockup - June 1991

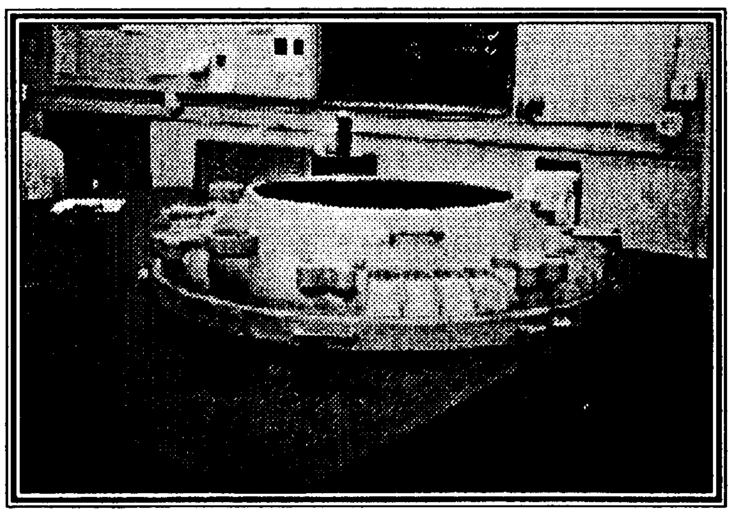
AFT MANIFOLD CASTING



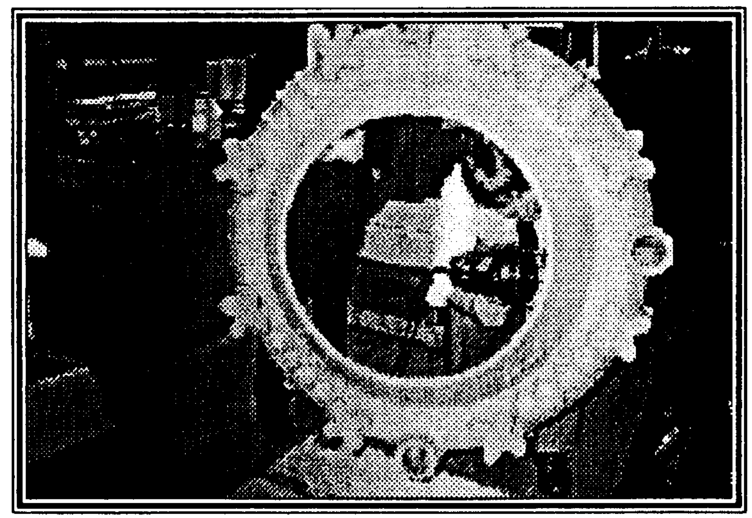
Weight = 705 lbs



3 inlets



Hung-On Test Bars



"Mint Flawless"

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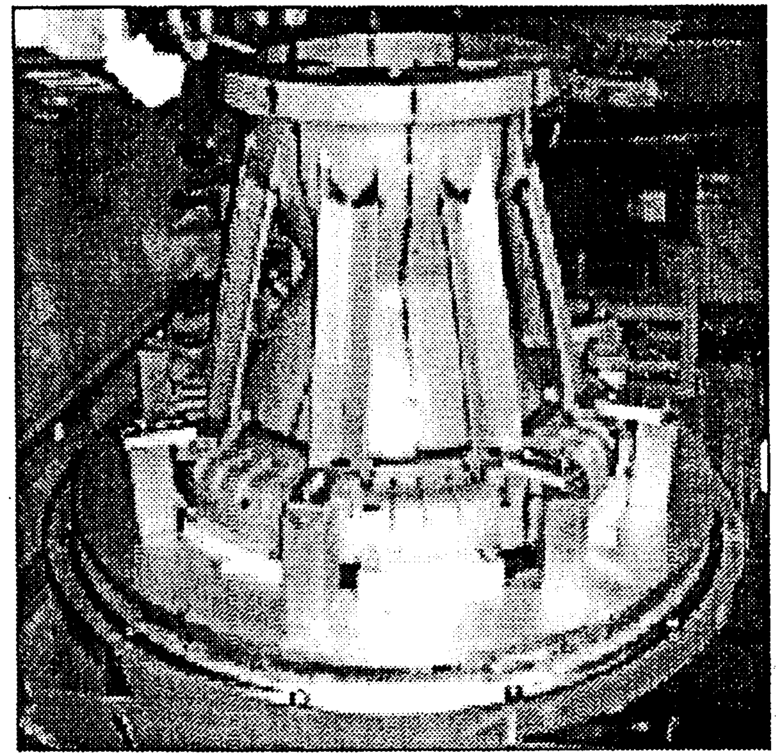
Rocketdyne Division

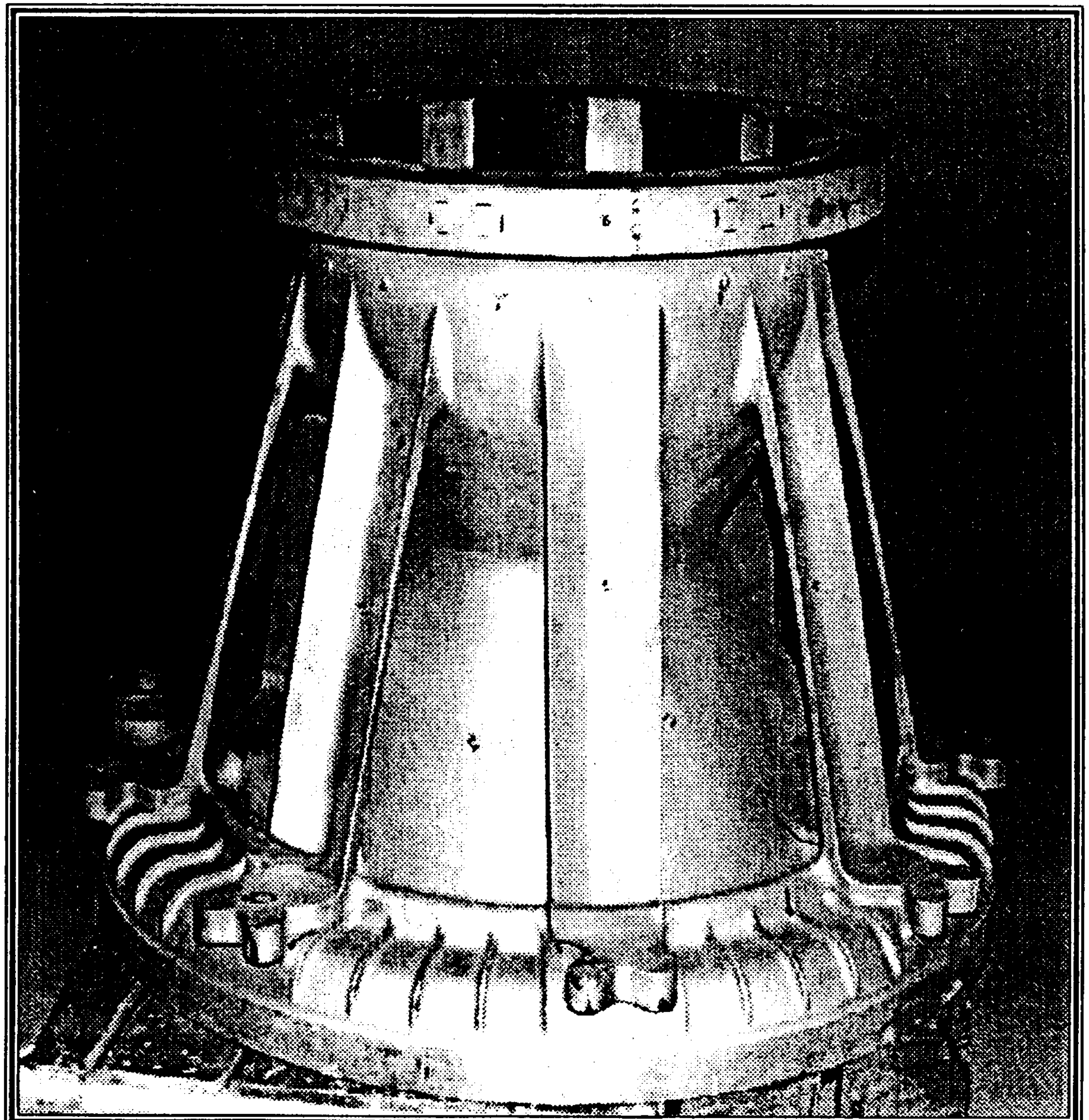
CAST JACKET WAX ASSEMBLY

1/8 Section Strut Positioned
Against Manifold Boss



Wax Welded Segments in
Assembly Fixture

JBK-75 STRUCTURAL CASTING ALLOY



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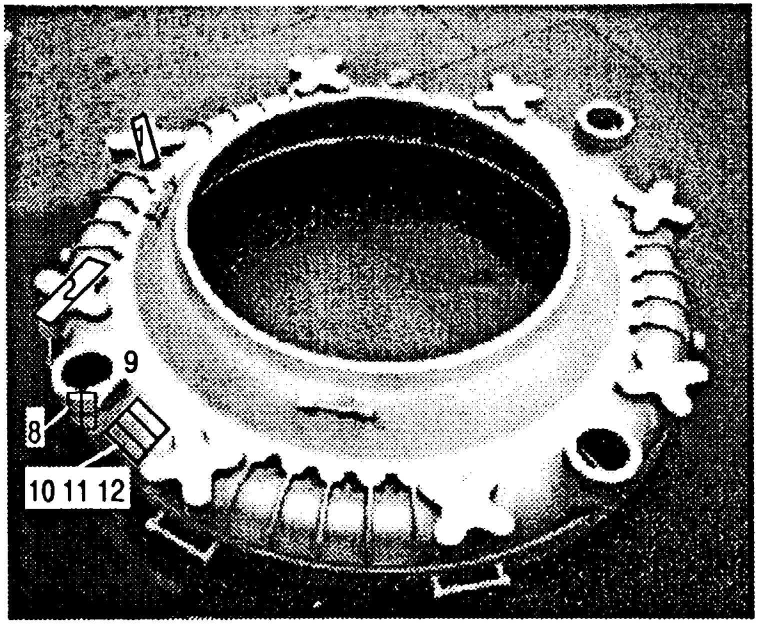
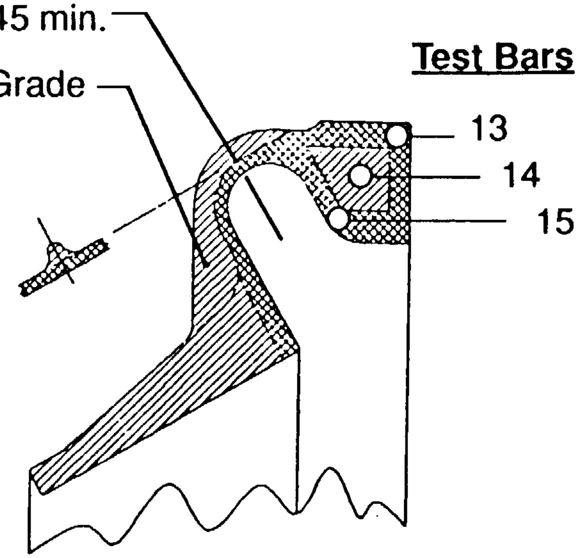
COMBUSTION CHAMBER AFT MANIFOLD CASTING
JBK-75 MATERIAL CHARACTERIZATION





Test Bar Locations

Bars 1 & 2 = Bosses
Bars 8 & 9 = Inlet
Bars 10, 11 & 12= Manifold
Bars 13, 14 & 15 = Heavy Manifold

Bars Cut From Section "A"

HIPped at 2050°F
Heat treated per RBO-160-078 - Rev. A

COMBUSTION CHAMBER AFT MANIFOLD
Room Temperature Tensile Data

Cut from casting (Koon-Hall Testing)

Bar No.	Location	U.T.S. (Ksi)	2% Y.S. (Ksi)	% El	% RA	R_C Hardware (3)	Grain Size	Intercept
1	Attachment Boss	128.8	99.6	24.0	28.5	30.5	M-11	.033 in.
2	Attachment Boss	127.1	98.4	24.5	37.0	30.5	M-9	.064 in.
8	Inlet Wall	135.1	105.4	20.0	34.0	28.5	M-8.5	.071 in.
9	Inlet Wall	133.5	104.8	22.0	40.5	29.5	M-9.5	.054 in.
10	Manifold Wall	117.0	101.0	20.0	40.5	29.0	M-7	.134 in.
11	Manifold Wall	123.4	99.6	18.5	21.5	30.5	M-7.5	.114 in.
12	Manifold Wall	126.7	101.6	27.5	43.5	32.0	M-7	.130 in.
13	Manifold Closeout	130.8	102.5	21.5	25.5	31.5	M-7.5	.111 in.
14	Manifold Closeout	121.2	96.0	19.5	46.0	29.0	M-9	.062 in.
15	Manifold Closeout	115.9	97.1	19.5	28.5	30.0	M-7.5	.098 in.
	Total Average	126.0	100.6	22.0	34.6	30.1		
	Total Std Deviation	6.2	2.9	3.1	7.8	1.1		
	Req'd by RBO-160-078 Rev. A	105	80	6	Report	Report		

COMBUSTION CHAMBER AFT MANIFOLD
Room Temperature Tensile Data Summary

Cut from casting	U.T.S.	2% Y.S.	% El	% RA	R_C Hardness
10 locations	ksi	ksi			
Total Average	126.0	100.6	22.0	34.6	30.1
Total Std Deviation	6.2	2.9	3.1	7.8	1.1
Hung-On-Bar	138.2	95.8	20.5	33.0	28.5
Req'd RBO-160-078 Rev. A	105	80	6	Report	Report

Heat Treatment:

2050 F - 1 hour in argon - FC @ '45 F/min. to 1000 F - air cool

+1380 F - 16 hours in argon - air cool

AFT MANIFOLD TEST RESULTS

- **Tensile properties**
  - Structurally important locations (10) - Excellent results
  - Largest grain size (3) - Location - Bar - 15 - Closeout section
    Bar - 10 - Manifold wall
- **Macrostructure**
  - Penetrant indications = minor only - surface connected shrink
- **Microstructure**
  - Carbides = Few scattered
  - Eta phase = Present (slow cool - segregation)
    Not resolutioned in heavy sections
- **JBK-75 = "Clean" alloy**
  - No significant metal - refractory reaction
    - Non-wetting

AFT MANIFOLD TEST RESULTS - (Cont'd)

- **Eta phase issue**
  - Eta phase — Ni_3Ti
    - Acicular (needlelike) precipitate which forms during solidification
    - More likely to form in areas rich in titanium
  - Previous experience
    - Always seen in as-cast JBK-75
  - Significant segregation occurred in thick sections of aft manifold
    - Titanium rich phase has lowest melting point, so collects in areas that solidify last
  - Eta phase concerns
    - Reduces ductility
    - Hydrogen embrittlement

CAST JBK-75 DEVELOPMENT ISSUES

- Mechanical properties - from castings
  - Tensile
  - Fracture mechanics
  - Fatigue
- Continue to verify microstructure in castings remains good
- Continue to examine composition, particularly in heavy sections
- In-process welding criteria and performance
- Verify that heat treatment of castings is correct
- HIP cycle optimization for full healing in thick sections

CAST JBK-75 LARGE STRUCTURE DEVELOPMENT ISSUES

- Evaluate effects of large grain size on casting performance
- Establish dimensional behavior in large parts
- Validate that NDE techniques will find any flaws larger than design specifications
  - Visual
  - FPI
  - X-ray
- Castability with reduced superheat
- Establish gating system
- Establish best process parameters and understand process limits

2.3.4 Vacuum Plasma Sprayed (VPS) Chamber Material/Process Development

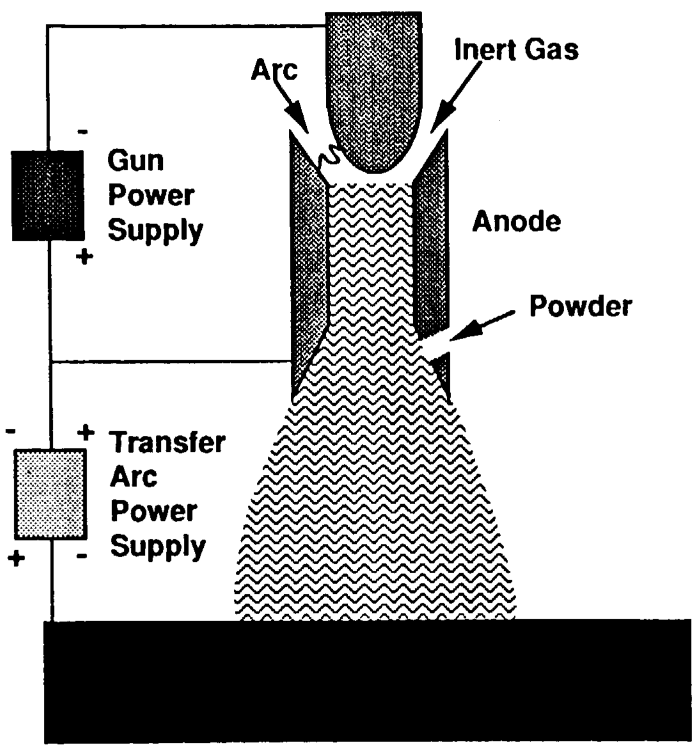
VPS COMBUSTION CHAMBER MATERIAL/PROCESS DEVELOPMENT CONTENTS

- **Process description**
- **Combustion chamber fabrication sequence**
- **VPS NARloy-Z development**
  - Material properties
  - VPS gun
  - Preheat system
  - Inspection
- **Hot-isostatically presses (HIP'ed) cold wall**
- **Channel filler development**
- **Summary of results**

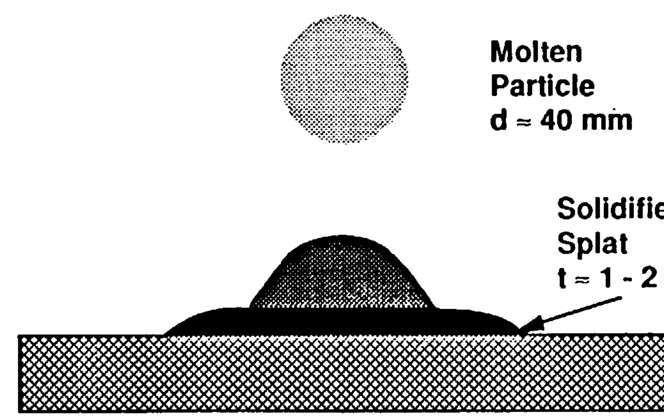
VACUUM PLASMA SPRAY TECHNOLOGY

- **Process**
  - High energy gas (plasma) used to deposit powders
    - Gas velocity > Mach 3
    - Powder size ≈ 40 microns
    - Powder temperature > melting point
  - Metals deposited - copper, NARloy-Z, Inconel 718
- **Advantages**
  - Clean, dense, adherent deposits
  - Near net shape process
  - Process amenable to automation
- **Limitations**
  - Process occurs in a vacuum chamber
  - High substrate temperature
- **Facilities**
  - General Electric Aircraft Engines

GUN SCHEMATIC / SPLAT SOLIDIFICATION

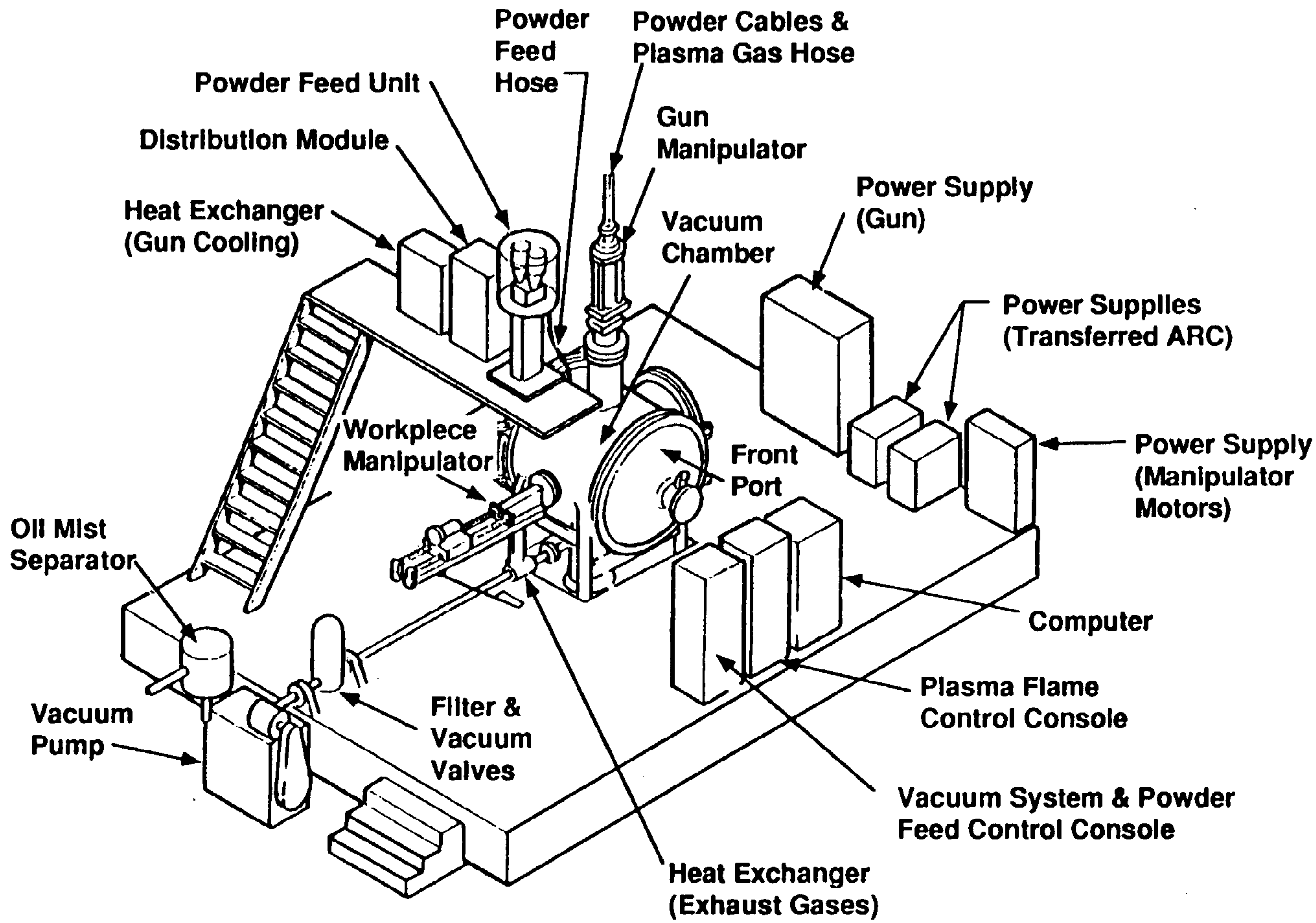


Gun Schematic



Solidifying Splat

VACUUM PLASMA SPRAY FACILITY



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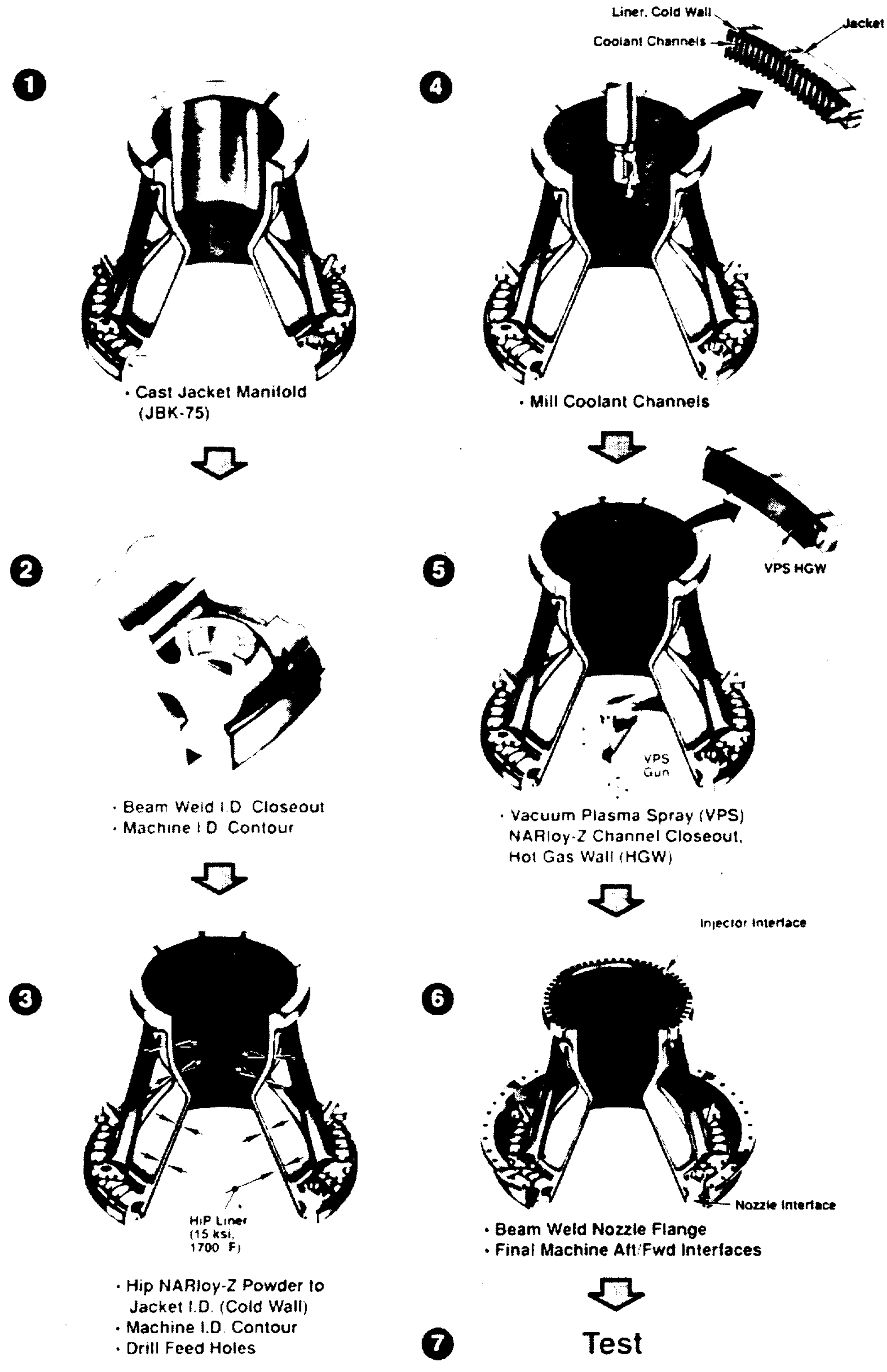
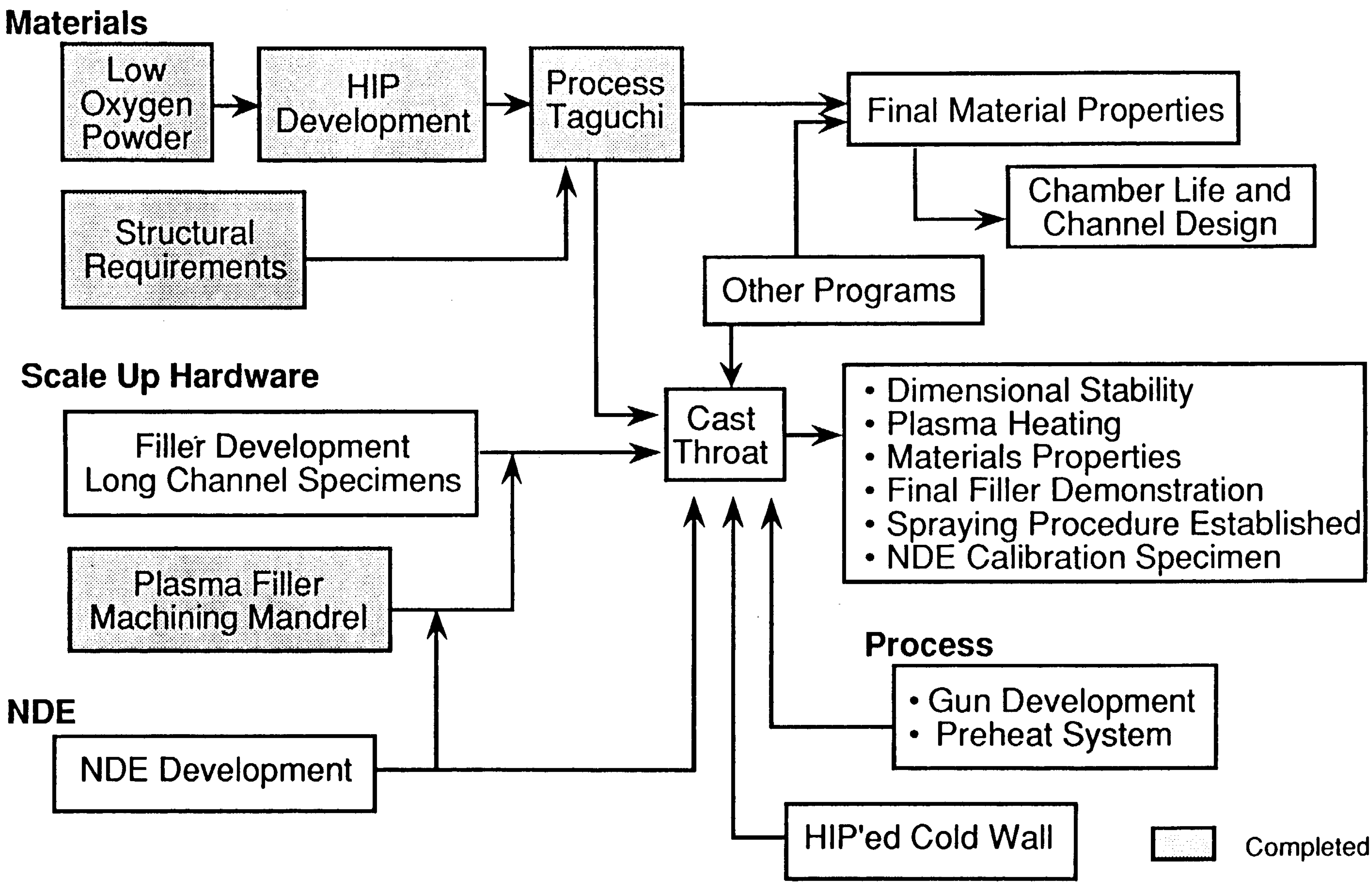
COMBUSTION CHAMBER FABRICATION SEQUENCE



VPS DEVELOPMENT LOGIC



MATERIALS DEVELOPMENT

- **Early work indicated low oxygen powder required**
  - Clean powder produced by Special Metals
  - Powder transferred anaerobically to VPS powder feeders
  - No oxygen pickup during plasma spray

- **HIP cycle optimization**
  - Improves strength and ductility, removes random porosity and improves bond qualities
  - Initial work explored only optimum temperature
    - 15 ksi maximum HIP pressure assumed
    - Six temperatures examined
    - Optimized temperature cycle

      1750 °F, +0 -25°F
      15 ksi
      3 hours

PRELIMINARY DESIGN VALUES

- **Tensile (at 1000 °F)**

UTS (ksi)	Yield (ksi)	El (%)	RA (%)
17.8	13.0	35.3	31.2

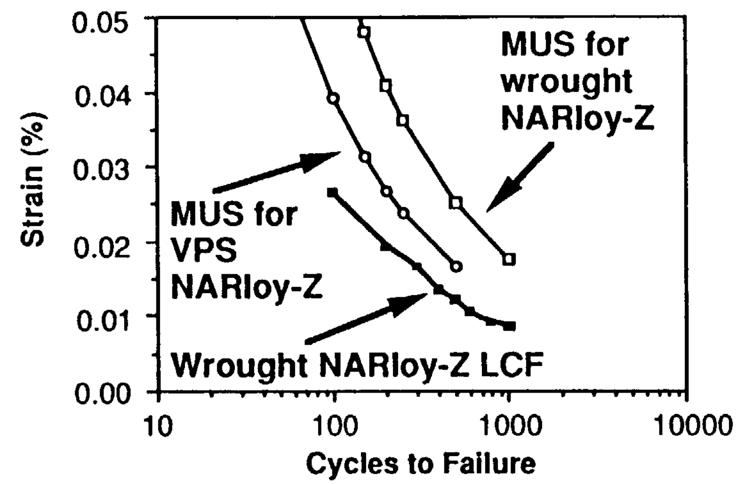
  - Values are for 2.0%Ag and 0.5%Zr in the deposit

- **Low Cycle Fatigue**
  - Values generated using Manson Universal Slopes (MUS)
  - Wrought NARloy-Z elastic modulus used
  - Wrought NARloy-Z used to anchor life predictions

- **Thermal conductivity is equivalent to wrought**

LOW CYCLE FATIGUE

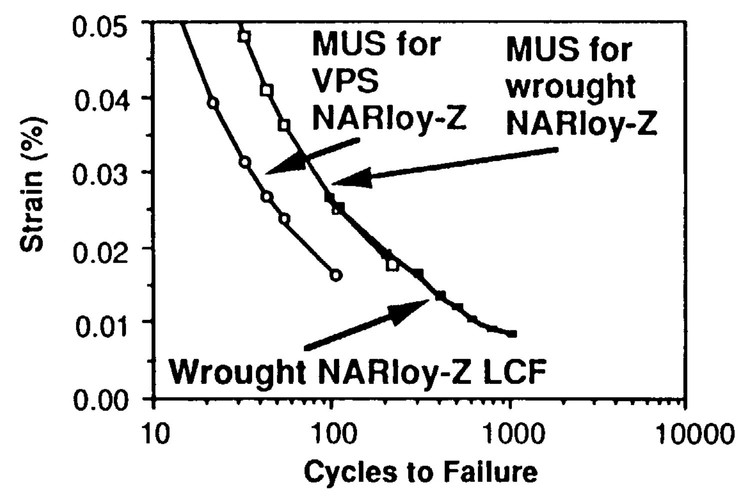
- Low Cycle Fatigue (LCF) based on Manson Universal Slopes
- Mean stress = 0; Mean strain = 0



Typical Values used in MUS calculations

	E (MSI)	UTS (KSI)	YS (KSI)	RA (%)
Wrought	10.7	20.9	16.1	55.0
VPS	10.7	17.8	13.0	31.2

Wrought NARloy-Z MUS life shifted to lower number of cycles to failure to match Wrought LCF life. VPS NARloy-Z MUS shifted by same amount



GUN DEVELOPMENT

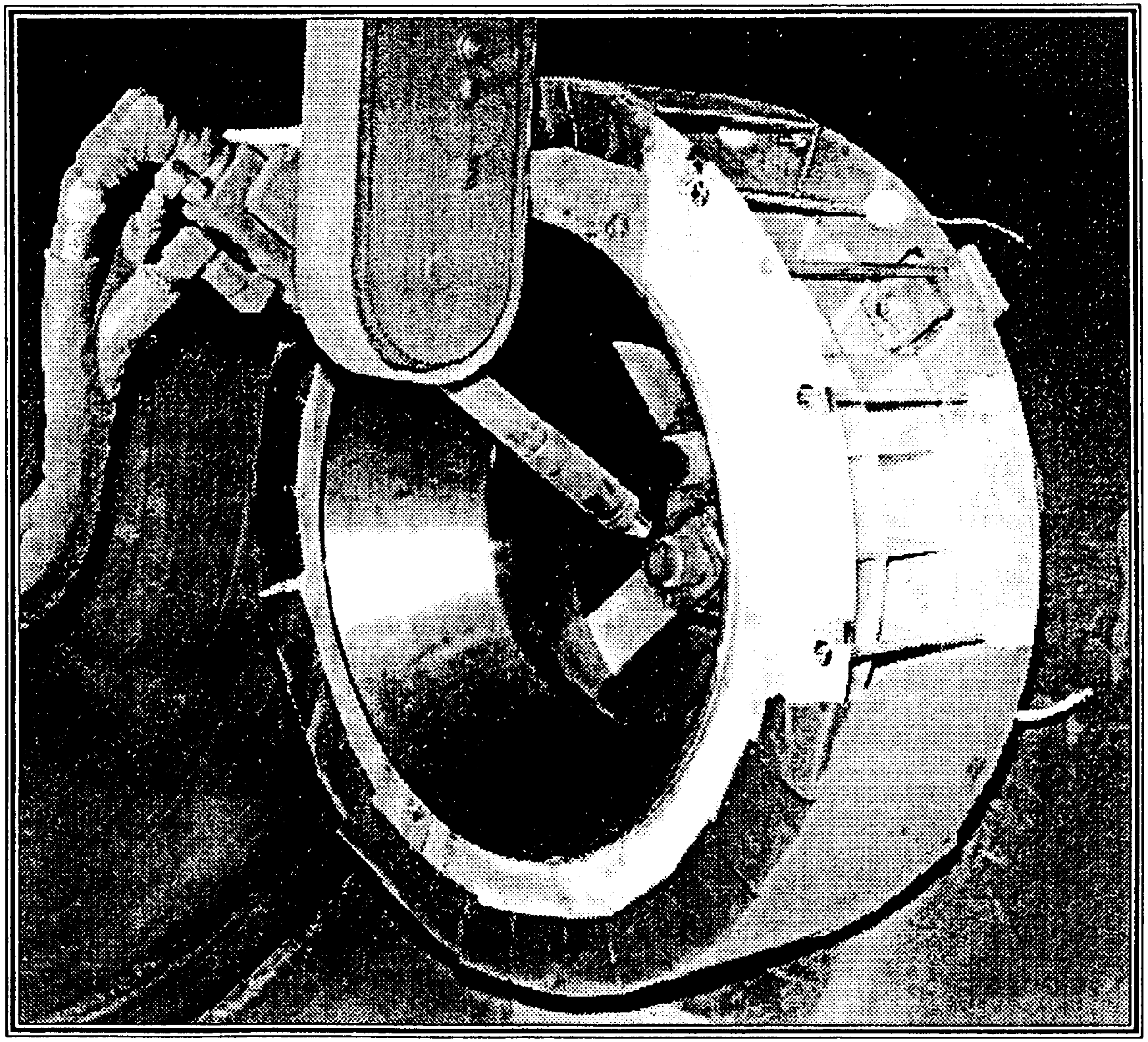
- **ID spraying**
  - Spraying work with the 60° gun has been stopped
    - Rapid erosion of the anode would limit gun on time
    - VPS deposits, although fully dense, had lower properties then with the 0° gun

- **New gun development**
  - The 0° gun is being repackaged into a smaller unit.
    - Repackaging of the existing plasma generation system into a 3 in. length
    - The new gun would use the existing anodes and powder injection system
    - Parameters developed for the 0° gun will be the same for the new gun

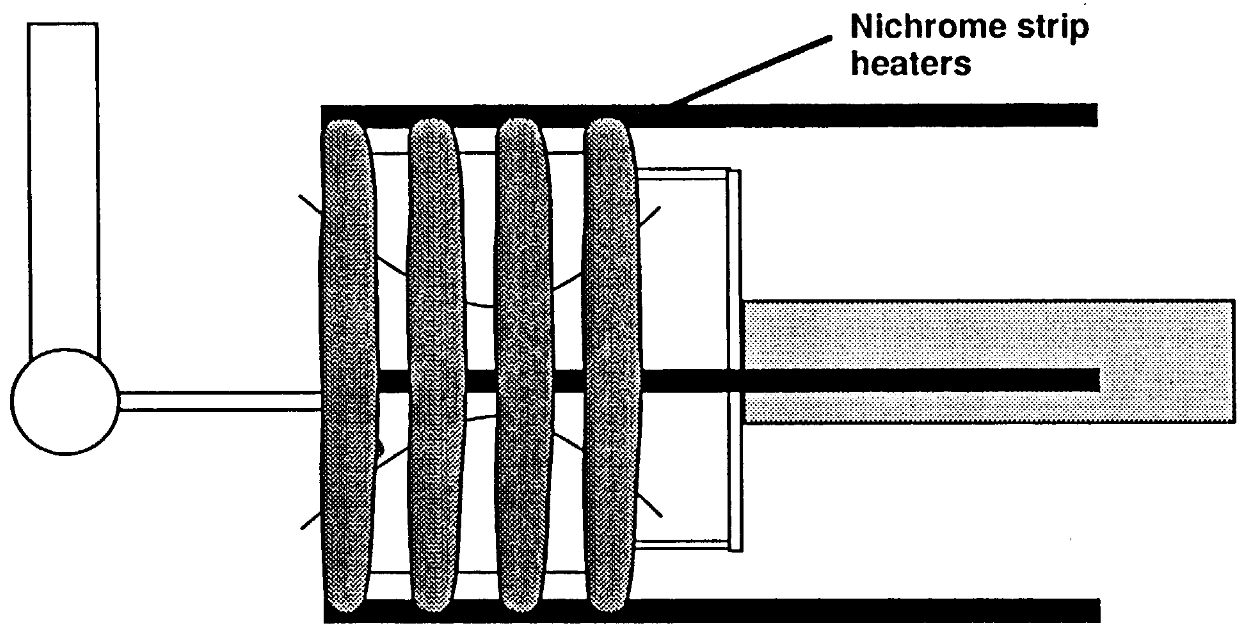
CAST THROAT PREHEAT SYSTEM

- **Preheat system**
  - Preheat system uses the plasma as one of the conductors to the heaters
  - Heaters rotate with the casting
    - 1.5 kw quartz heaters were used
- **System test results**
  - Maximum temperature reached 1450°F
  - Additional power input would not have helped
    - At power level use ≈ 15 kw arc were striking from the plasma to the casting, causing local melting
  - No distortion induced by preheat
- **New system proposed**
  - A new system to be installed in which the casting rotates within the heaters

CAST THROAT IN VPS TANK



NEW PREHEAT SYSTEM

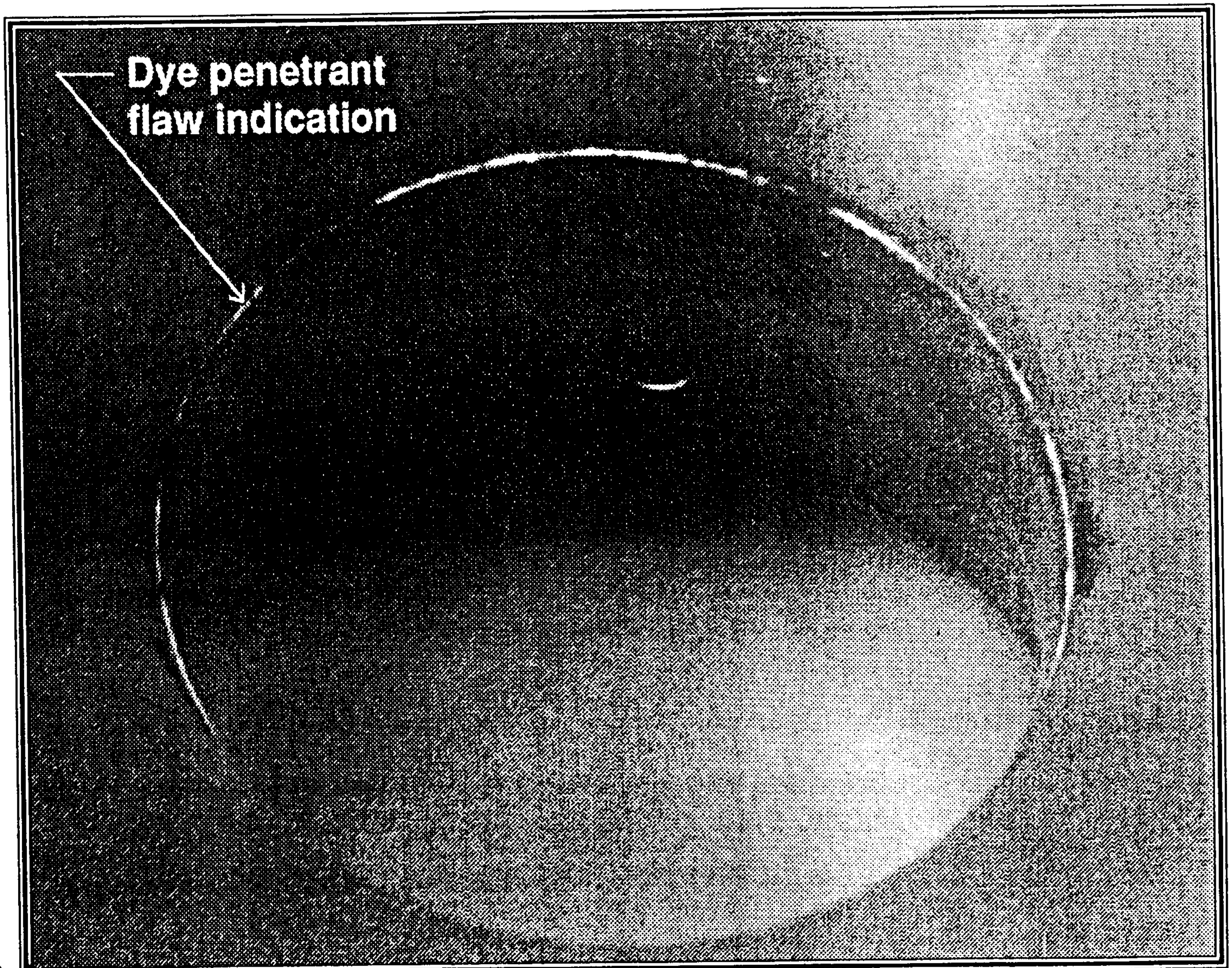


- Power is transmitted to the nichrome heaters through feed throughs in the tank
- Heating is controlled by thermocouples on the throat
- Insulation would be wrapped around the nichrome to reduce radiation to the tank

NDE SURFACE FLAW DETECTION

- **40K IR&D hardware at GEAE had a known surface flaw**
  - 40K hardware sprayed at GEAE had a known bond line/ surface flaw in the throat
  - Dye penetrent inspection had indication for only this location
- **Eddy current inspection**
  - Eddy current easily located the flaw in the throat
  - No other flaws were found
- **Results**
  - Eddy current appears to detect surface flaws without the contamination problem
  - Resolution of the technique requires development

40K IR&D COMBUSTION CHAMBER



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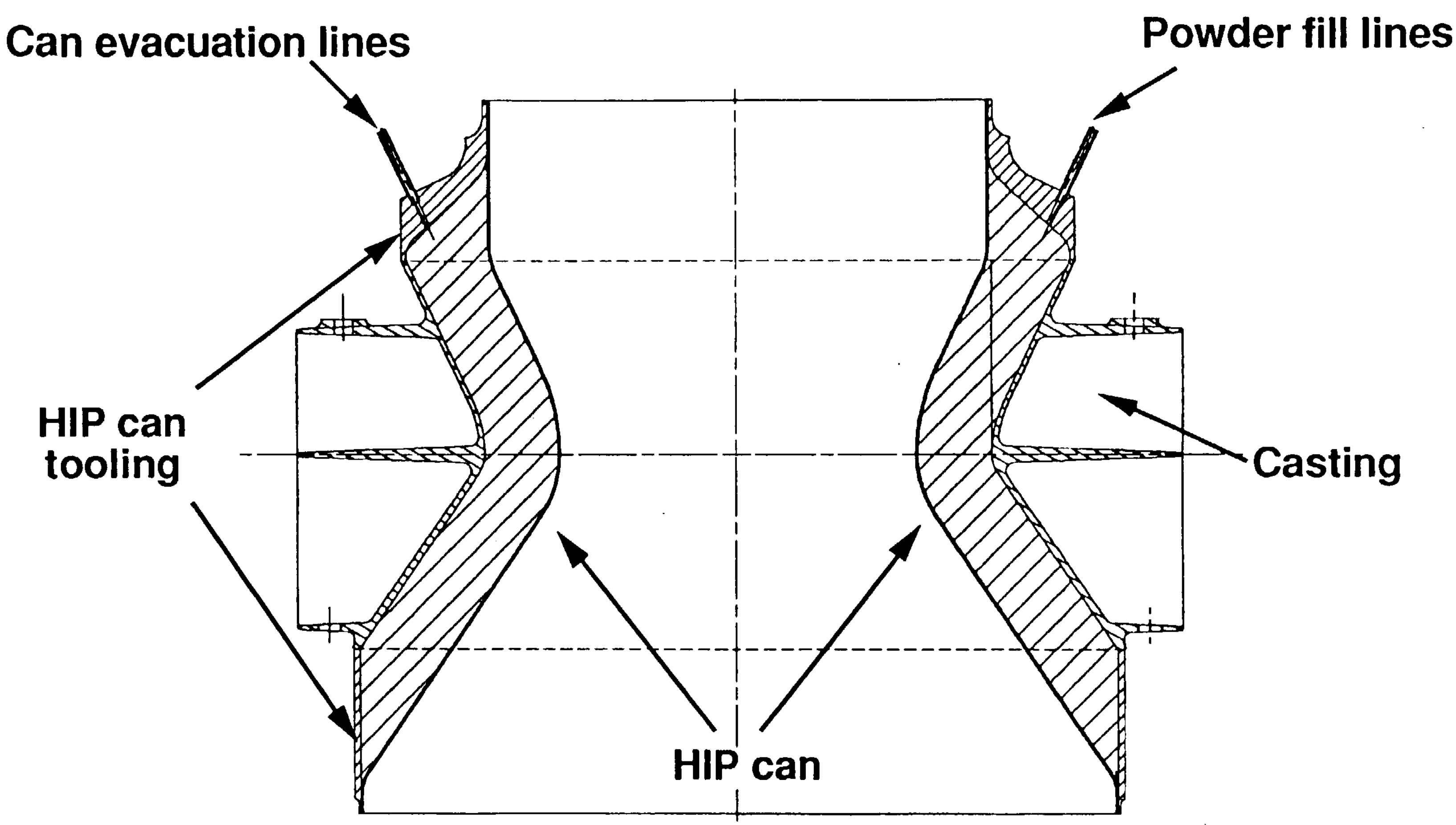
CHANNEL ROUGHNESS NDE

- **Ultrasonic inspection for hot wall roughness**
  - 0.035 in. sheet of VPS NARloy-Z was machined and etched to simulate channel hot wall roughness
  - Roughness varied from 18 to 88 ra with one section at 170 ra

- **Inspection results**
  - 170 ra line easily distinguishable
  - Gradient in response signal obtained from the other section

- **Further testing**
  - Additional work will be done to try and calibrate the response

HIP'ed COLD WALL CONCEPT

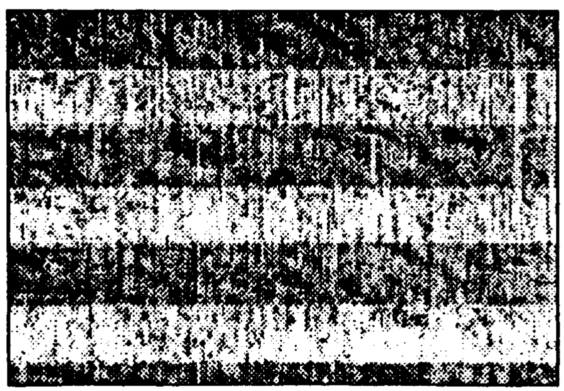


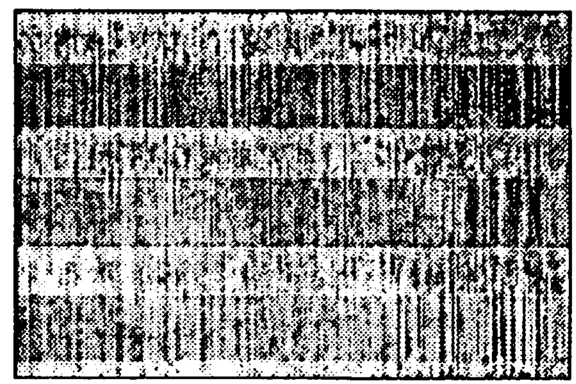
HIP'ed COLD WALL

- **Preliminary materials properties obtained**
  - Direct HIP NARloy-Z looks very promising
    - UTS - 19 ksi, YS - 11 ksi, %El - 28%, %RA - 29%
  - Testing of JBK-75 HIP bond to NARloy-Z powder is in work

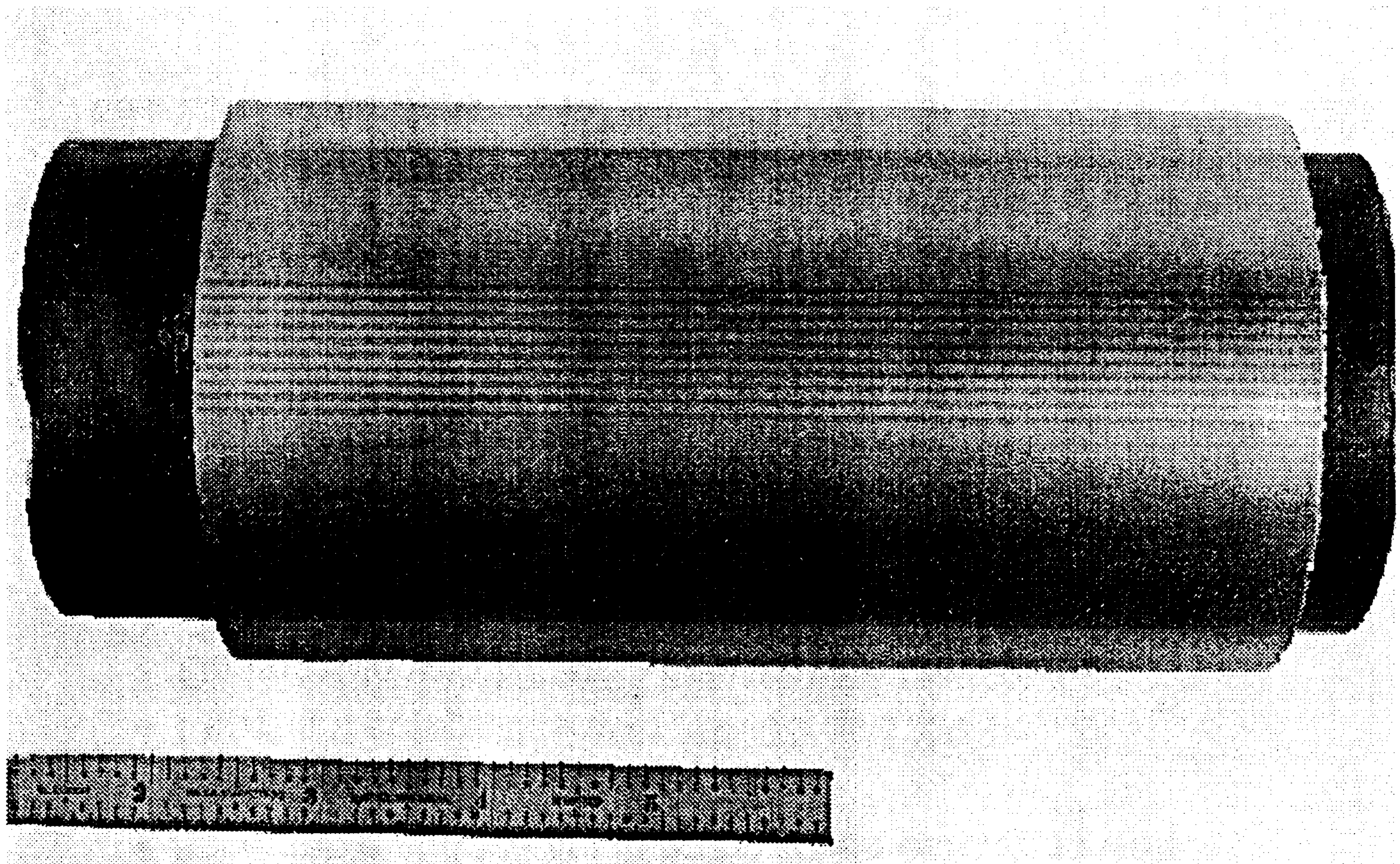
FILLER DEVELOPMENT

- **Leachable filler requirements**
  - Acceptable surface finish on backside of hot gas wall
  - Easily leachable
  - Leachant compatible with JBK-75 and NARloy-Z
  - Compatible with NARloy-Z deposition temperature
  - Cost effective to install and remove
- **Machining parameters developed to minimize smearing**





FILLER DEVELOPMENT SPRAY MANDREL



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FILLER REMOVAL NDE

- **Eddy current inspection for VPS iron filler**
  - A section of channeled and closed-out VPS NARloy-Z plate with VPS iron filler was used for filler removal inspection
  - Hot wall thickness was approximately 0.035 in.
  - The plate contained a channel width transition from 0.040 to 0.050 in.
- **Inspection results**
  - The VPS iron was easily detectable
- **Further testing**
  - The filler will be removed in steps to determine the effectiveness of the inspection technique

SUMMARY OF ACCOMPLISHMENTS

- Preliminary VPS NARloy-Z properties obtained
- HIP cycle development complete
- NDE - Eddy current effective for surface flaws
- Preheat system worked but did not reach full temperature
- Gun development started
- Sprayed iron filler successfully leached out of test specimens

2.3.6 COMBUSTION CHAMBER RESULTS

- **Preliminary design and analysis of two concepts**
  - Liquid interface diffusion bonded (LIDB) liner with electrodeposited nickel-cobalt (EDNiCo) structure
  - Vacuum plasma sprayed (VPS) liner with full cast jacket
- **Produced large structural castings**
  - Cast JBK-75 exhibited very good properties with excellent castability and weldability
  - Aft manifold casting passed production NDE
  - Integral jacket was largest aerospace-quality vacuum investment casting produced to date
- **Significant VPS NARloy-Z copper alloy development results**
  - Preliminary properties obtained
  - Many process parameters identified

2.4 NOZZLE

The SSME nozzle was analyzed in detail to determine cost and reliability drivers. The SSME nozzle is fully regenerative cooled with high pressure liquid hydrogen. The hydrogen feedline enters a manifold at the base of the nozzle which distributes the coolant to the liner tubes which in turn feed a forward manifold and outlet line. This type of nozzle was required for the SSME staged combustion cycle which gives high performance. To fabricate the nozzle, tubes which vary in diameter and wall thickness are specially shaped to make the bell curve of the nozzle. The tubes are then brazed together by laying braze alloy and stacking each tube one at a time before furnace brazing. The rest of the nozzle fabrication utilizes machined forgings with a high number of welds.

The largest experienced problem with the SSME nozzle is coolant tube leakage. After repeated hot-fires, small leakes develop in the tubes and have to be repaired if the leakage is too severe. Another concern includes the high pressure circuitry required in the hydrogen coolant system. The nozzle flexes considerably during startup and shutdown which flexes the high pressure feed lines (which have failed in the past). The need for hydrogen embrittlement protection for the Inconel 718 used in the coolant circuit is also of concern.

As in other components, the SSME nozzle contained a high number of parts that are joined together. The nozzle requires a high amount of manual labor for brazing the tubes and welding the post-braze assembly. The complexity of the manifolding also required significant amounts of machining.

To lower the cost of the nozzle the welding and braze operations would have to be drastically reduced and the feed circuitry would have to be simplified. Reducing the part count and joining operations through the use of investment castings would help, but the nozzle liner is a special problem. What helps the situation is the gas generator (GG) type engine cycle used by the STME. The relatively cool, low pressure GG exhaust gas could be used to cool the nozzle wall. This allows use of cheaper tubing or sheet metal liner materials. Process automation would also help reduce costs. For example, hypervelocity sprayed (HVS) material could be used as the supporting structure to the liner - where much of the machining and manual welding is required on the SSME nozzle.

Reliability of the nozzle would be enhanced by significantly lowering the coolant circuit pressure by using the GG exhaust gas. This coolant method would also simplify the coolant circuit and allow for lower strength, hydrogen embrittlement resistant materials such as Inconel 625.

The charts that follow describe in detail the work associated with the nozzle design effort. The agenda is listed below:

- 2.4.1 Concept Selection
- 2.4.2 Design and Analysis
  - Design Configuration
  - Structural Analysis Results
  - Film Cooling Analysis
  - Aerothermal Analysis
  - Cost Summary
- 2.4.3 Hypervelocity Sprayed (HVS) Nickel Alloy 625
- 2.4.4 Nozzle Results

2.4.1 CONCEPT SELECTION

BASELINE – 1 TURBINE EXHAUST COOLED NOZZLE

NOZZLE COST DRIVERS

- **SSME cost drivers**
  - 45% post braze assembly
    - Manual welding
  - 26% braze operations
    - Apply alloy, stack tubes, braze
  - 20% add manifolds to jacket assembly
    - Machining; welding
  - 9% jacket assembly
- **Cost reduction methods**
  - Dramatically reduce
    - Welding
    - Feed circuitry
    - Braze operations
  - Simplify design
    - Cast manifolds
    - HVOF jacket
    - Constant dia./thickness coolant tubes
      - Formed by booking
  - Automate processes

NOZZLE RELIABILITY DRIVERS

- **SSME nozzle reliability concerns**
  - High pressure fuel circuitry
  - Tube leaks
  - Hydrogen embrittlement protection (Inconel 718)
- **Reliability/margin improvements**
  - Eliminate feedlines/steerhorns
  - Significantly lower circuit pressure
  - Eliminate Inconel 718
    - Use Inconel 625

NOZZLE DESIGN CRITERIA

Engine thrust	580,000 lbs
Throat diameter	13.14"
Chamber exit diameter	35.30"
Nozzle attach area ratio	7
Nozzle exit area ratio	40
Nozzle exit diameter	84.04"
Nozzle length	83.45"
Turbine exhaust gas parameters @ manifold entrance	
Flowrate	54 lb/s
Temperature	1100 R
Pressure	150 psi
Mixture ratio	0.876
500th unit cost	<$400,000
Reliability	0.99986
Weight	1700 lbs
Life	15 cycles with factor of 4
Safety Factor	1.1 yield, 1.5 ultimate

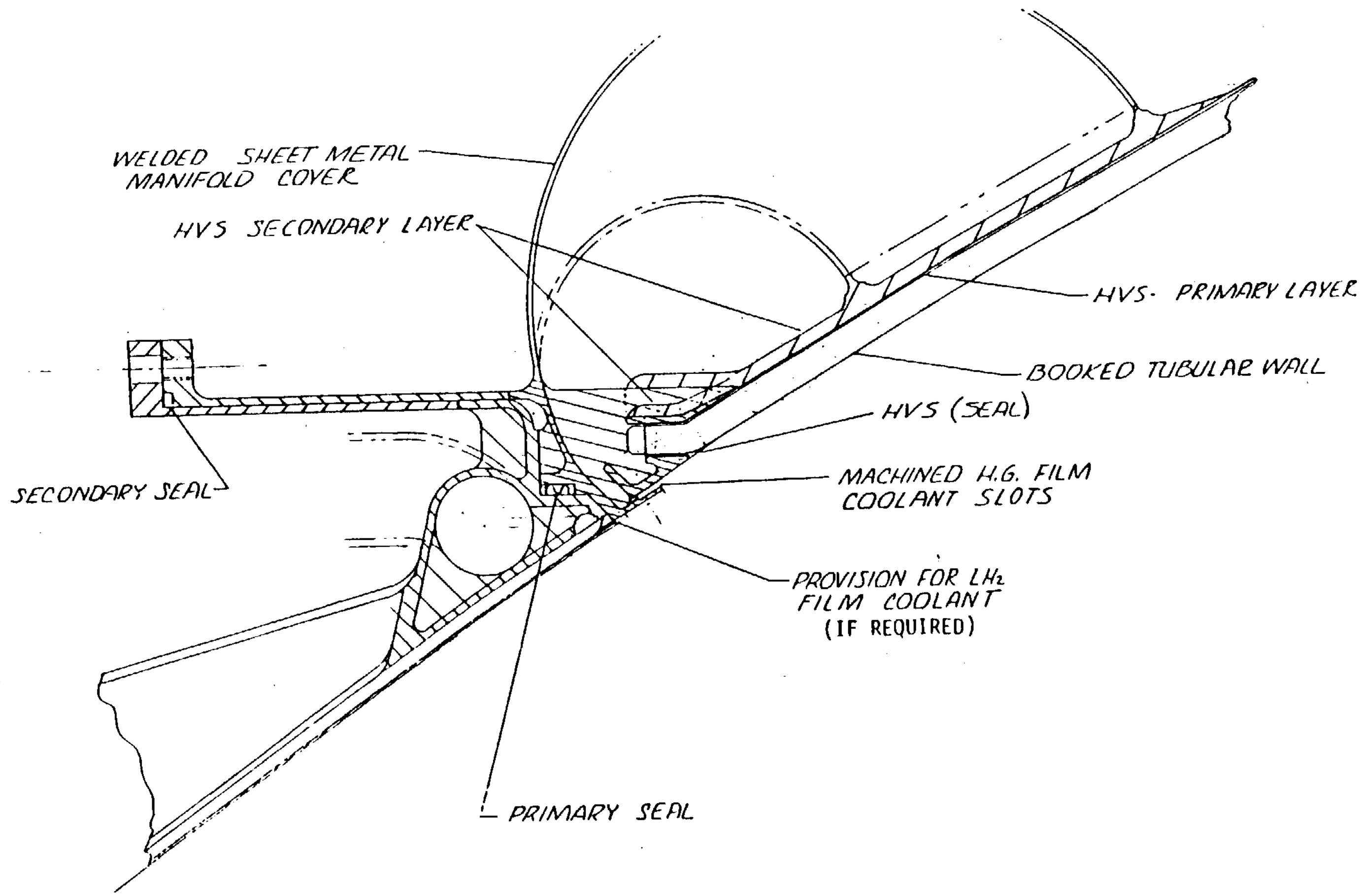
Nozzle must support the weight of the entire engine assembly

NOZZLE DESIGN CONCEPTS EVALUATED

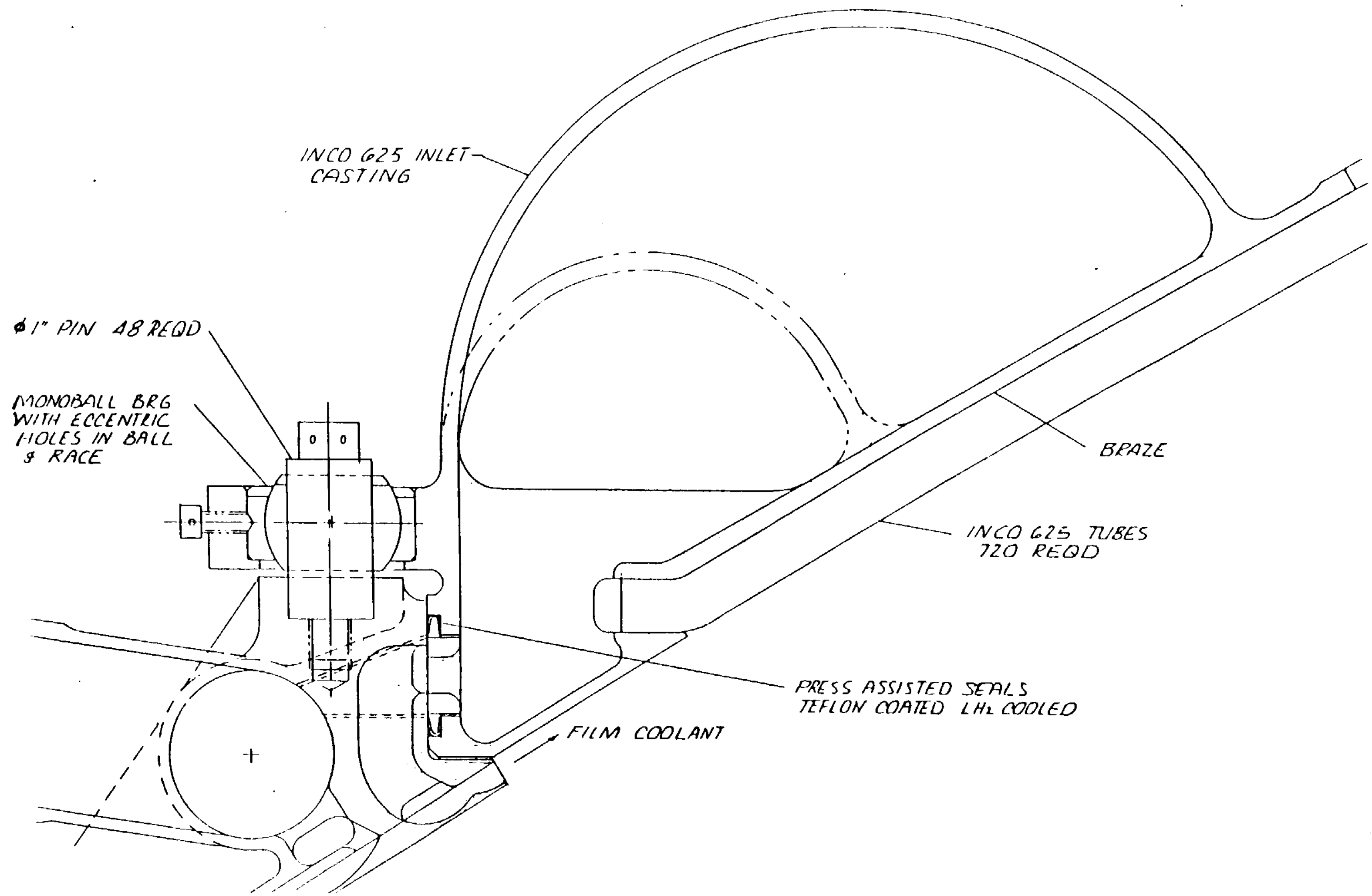
Description	Advantages	Disadvantages
HVS Gas Cooled Tube Nozzle (film/convective)	Eliminates brazing operations	Material properties and development required
Braze gas Cooled Tube Nozzle (film/convective)	Low risk manufacturing techniques	Braze operations, jacket structure
Regenerative Two-Pass tube HVS Jacket	Eliminates brazing, some increase in performance	Additional manifolds, tube costs
Transpiration Cooled Nozzle Double Wall	Relatively simple construction reliable	Requires high coolant flow and performance loss
Carbon/Carbon with/without Film Cooling	Few components, light weight	High cost, radiation cooled, tooling unavailable
HVS Gas Cooled Channeled Nozzle	No brazing, few components	Heavy, labor intensive
Convolute Passage Gas Cooled Nozzle (film/convective)	Low cost	Endurance questions, development required

Selected

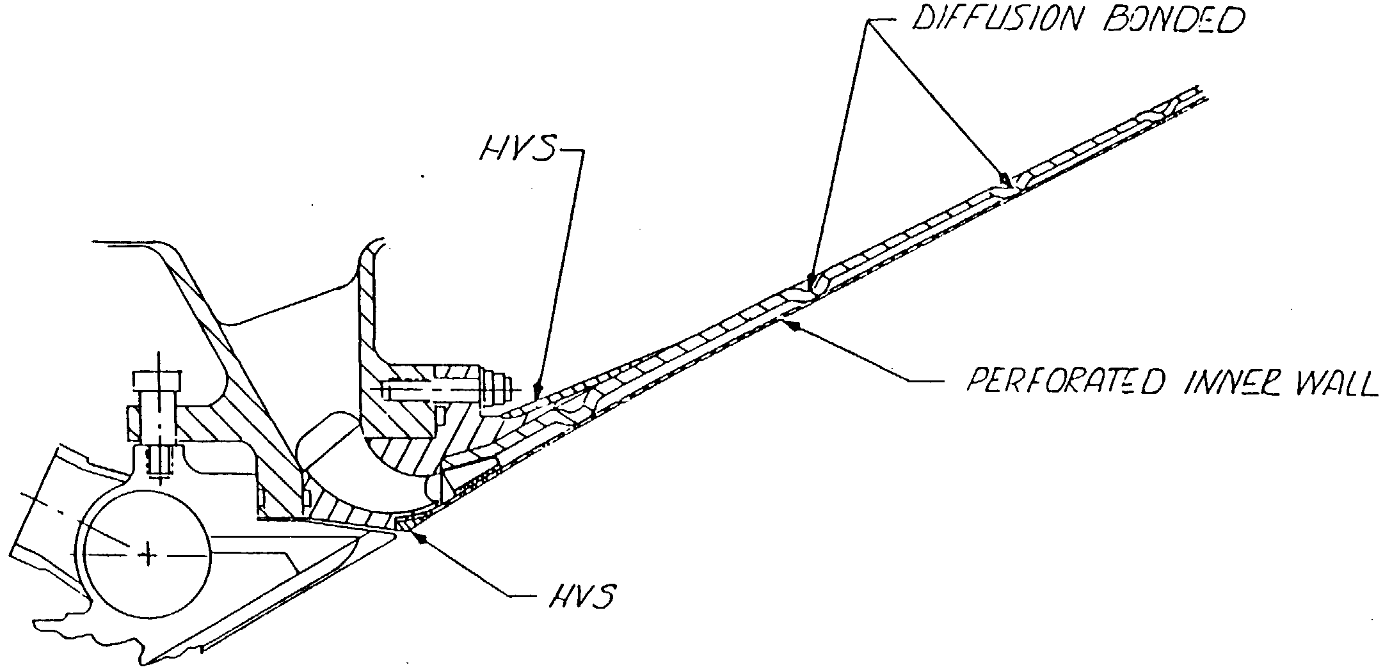
HVS GAS COOLED TUBE NOZZLE CONCEPT



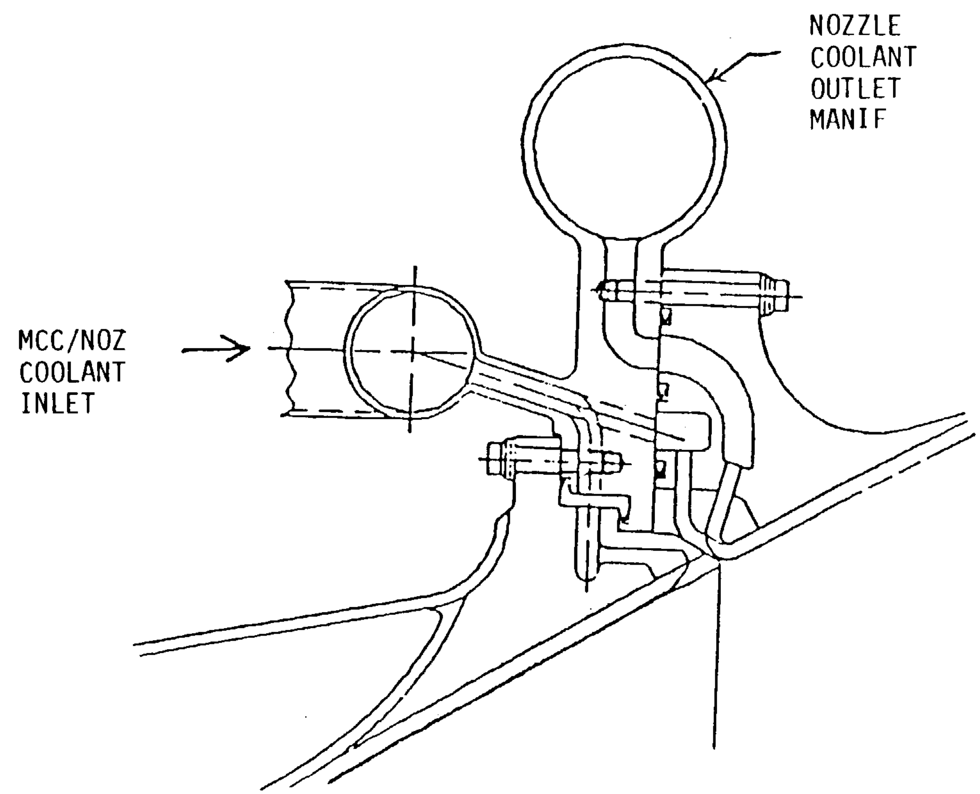
BRAZE GAS COOLED TUBE NOZZLE CONCEPT



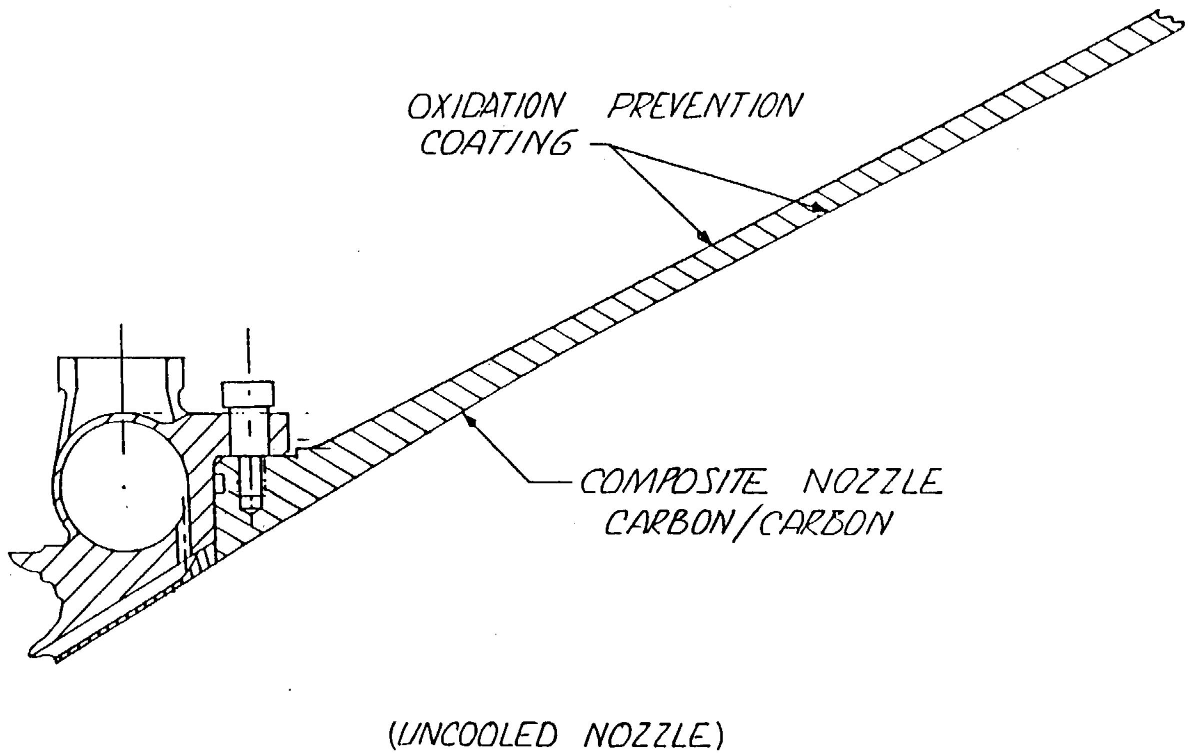
TRANSPIRATION COOLED NOZZLE CONCEPT
(Double Wall)



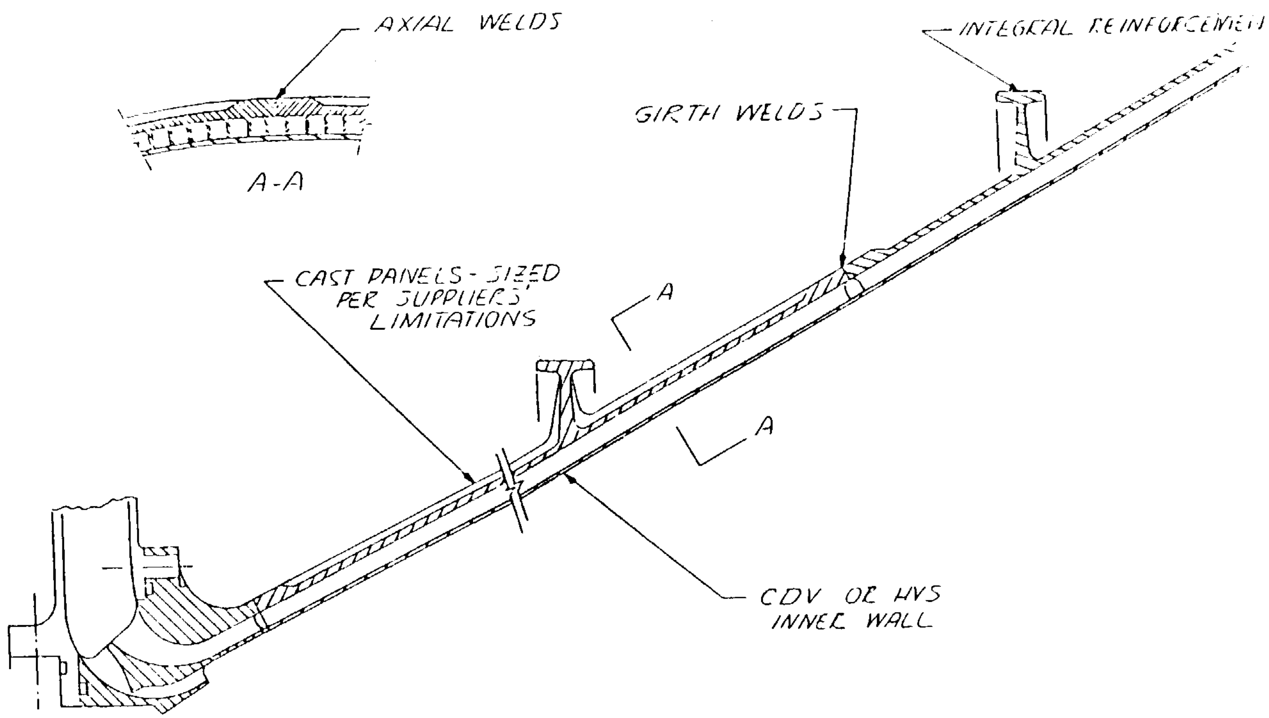
REGENERATIVE TWO-PASS TUBE HVS JACKET NOZZLE CONCEPT



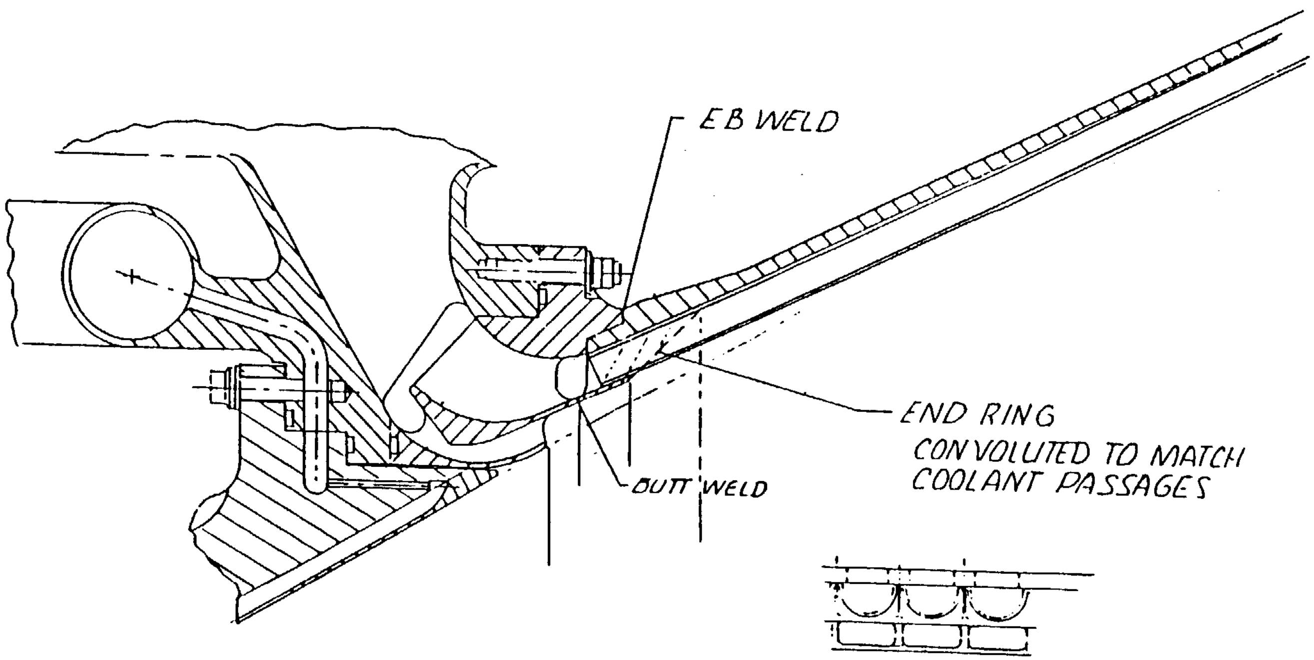
CARBON/CARBON NOZZLE CONCEPT
(Film Cooling Optional)



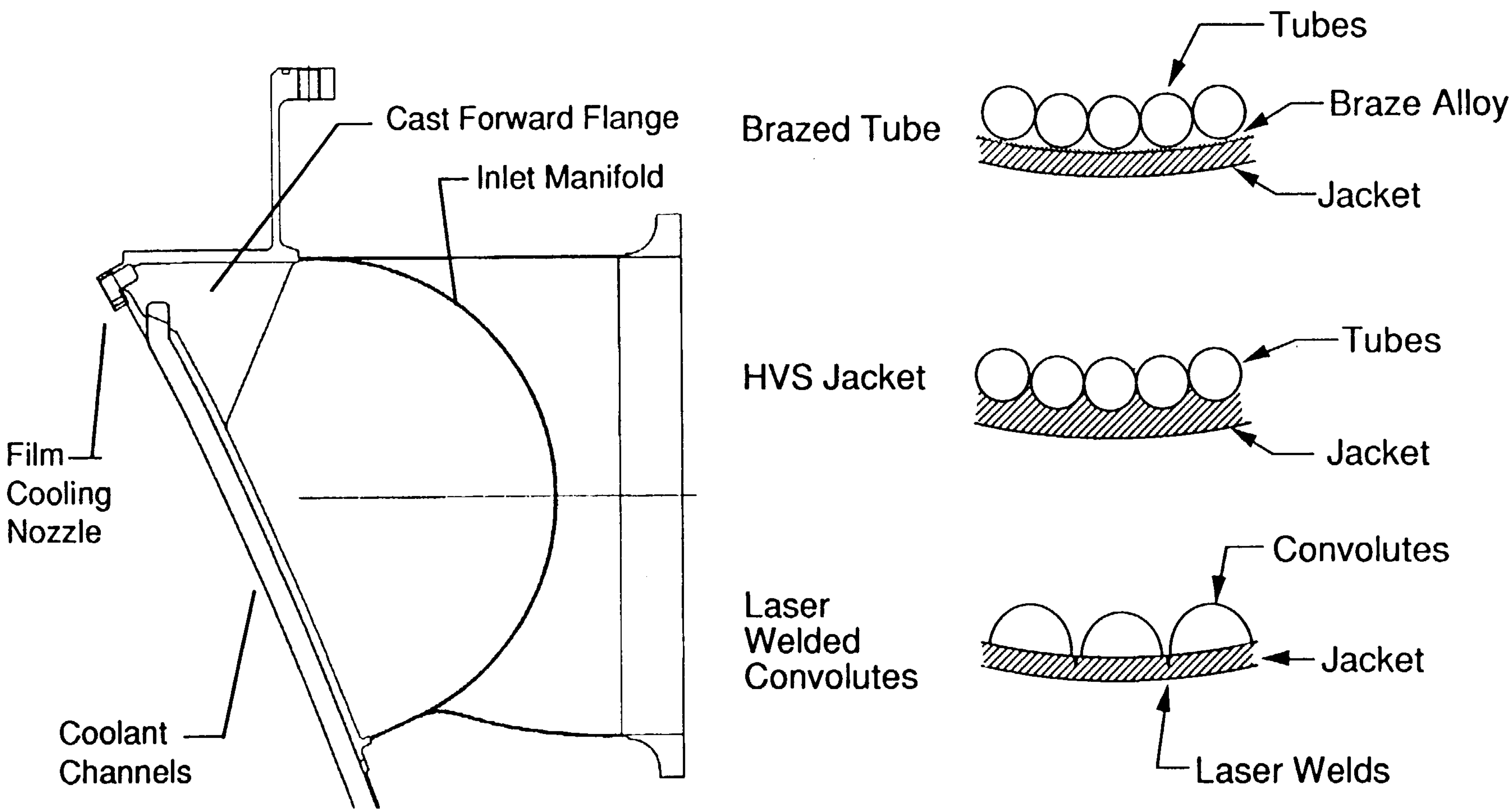
HVS GAS COOLED CHANNELED NOZZLE CONCEPT



CONVOLUTE PASSAGE GAS COOLED NOZZLE CONCEPT



MOST PROMISING TURBINE EXHAUST GAS COOLED NOZZLE CONCEPTS



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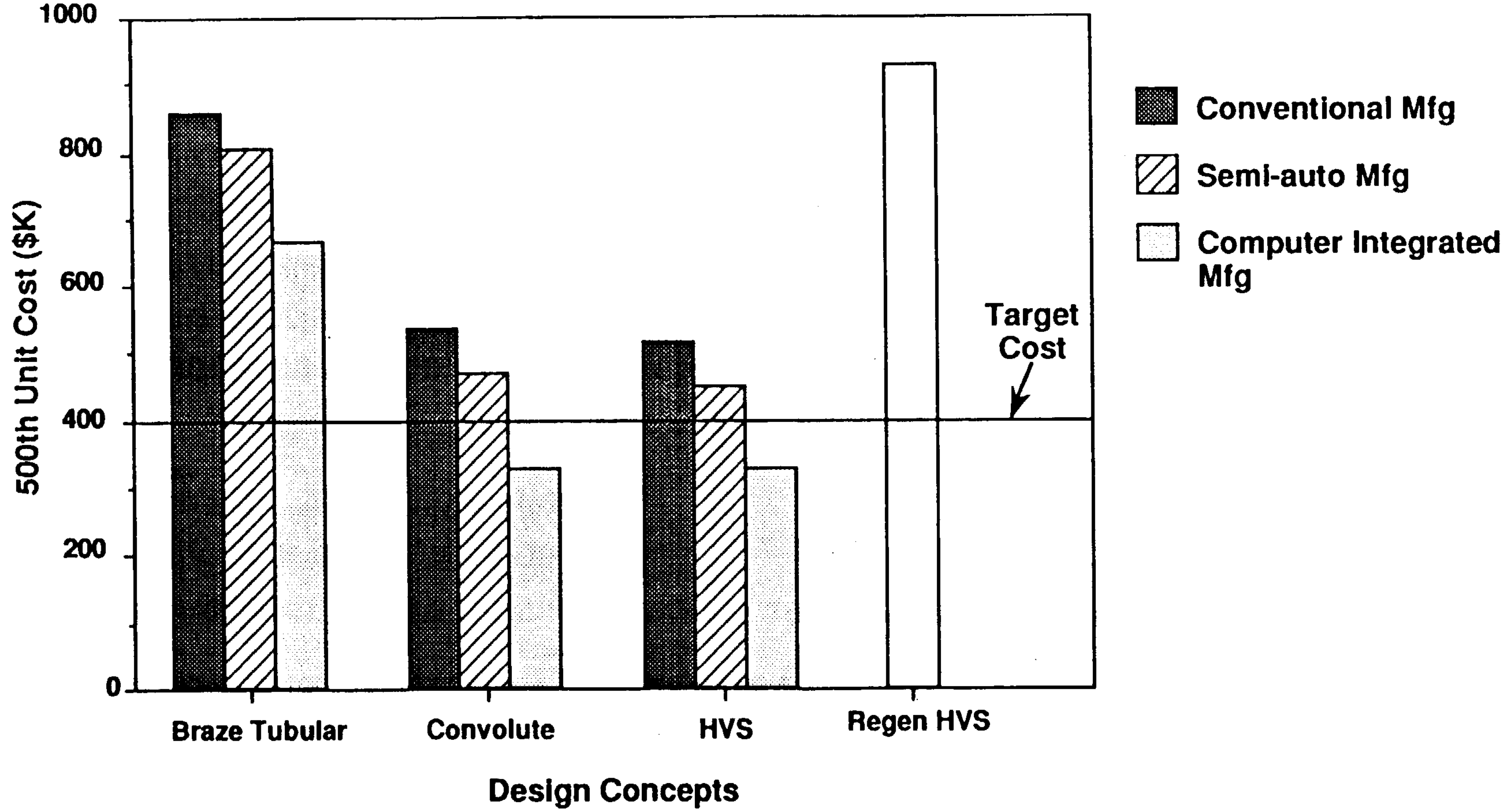
TURBINE EXHAUST GAS COOLED NOZZLE CHARACTERISTICS

Concept	Advantages	Disadvantages
Brazed Tube (weight ≈ 1600 lbs)	• Extensive technology base	• More expensive than other concepts
HVS Jacket	• Low cost • Eliminates alloy	• Process not developed • Fabrication facility does not exist • Heavier than other concepts
Convolute Liner (weight ≈ 1400 lbs)	• Low cost • Eliminates tubes and alloy • Prior experience with explosive forming • One piece coolant liner	• Application not developed • Requires weld inspection • Larger interstice volume than tubes

NOZZLE COST COMPARISON

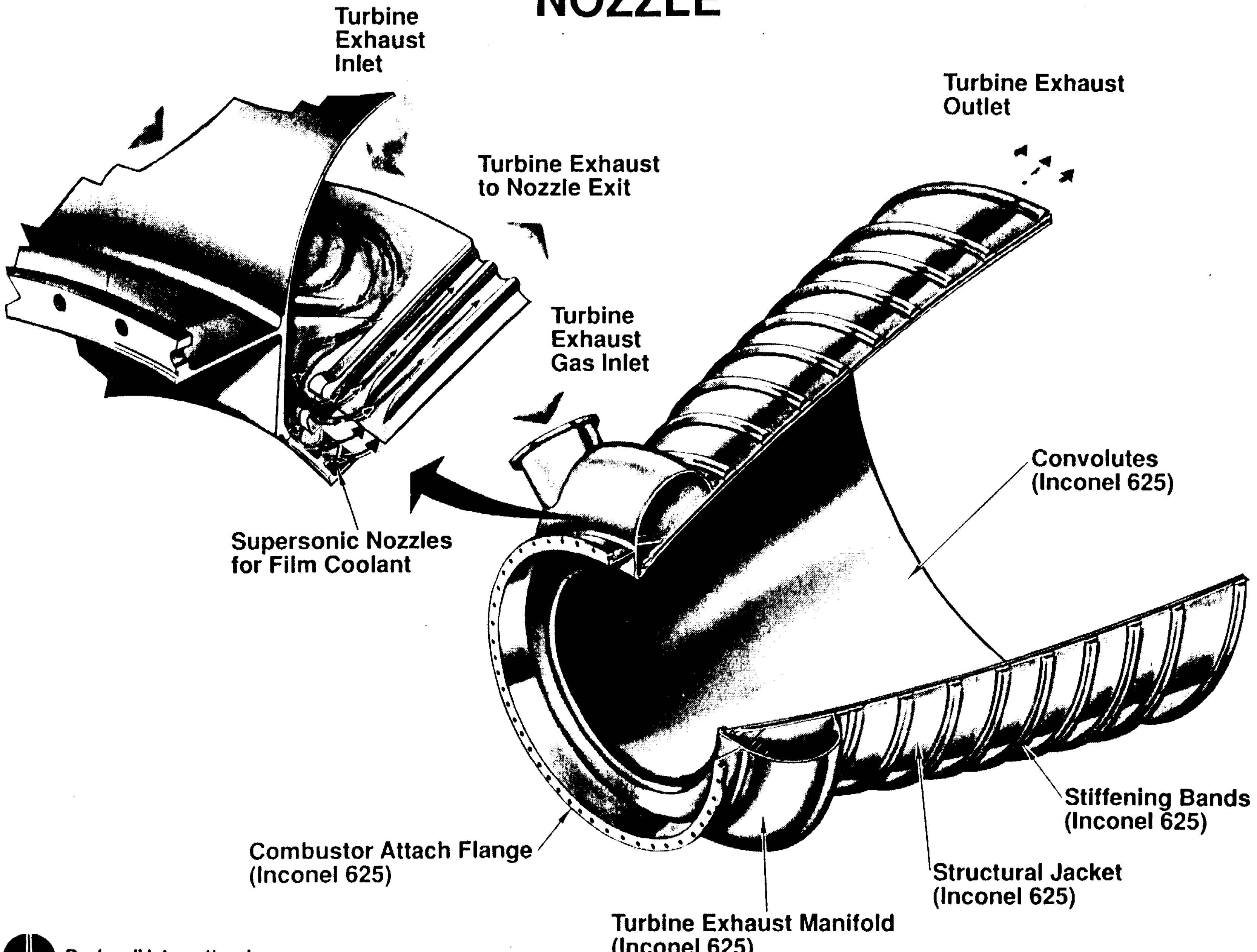


NOZZLE CONCEPT SELECTION
Summary

- **Analysis has shown feasibility of turbine exhaust gas cooled nozzle**
- **Laser welded convolute nozzle selected as fabrication technique for ADP**
  - Feasibility of concept identified
  - 500th unit cost is below target
- **Rationale for deletion of other concepts**
  - HVS process ruled out due to cost and process development risk
  - Brazed nozzle substantially over cost target
  - Regen nozzles
    - Concepts over cost target
    - Technique required for removal of turbine exhaust gases
    - Weights between 1700 and 1850 lbs

2.4.2 DESIGN AND ANALYSIS

NOZZLE



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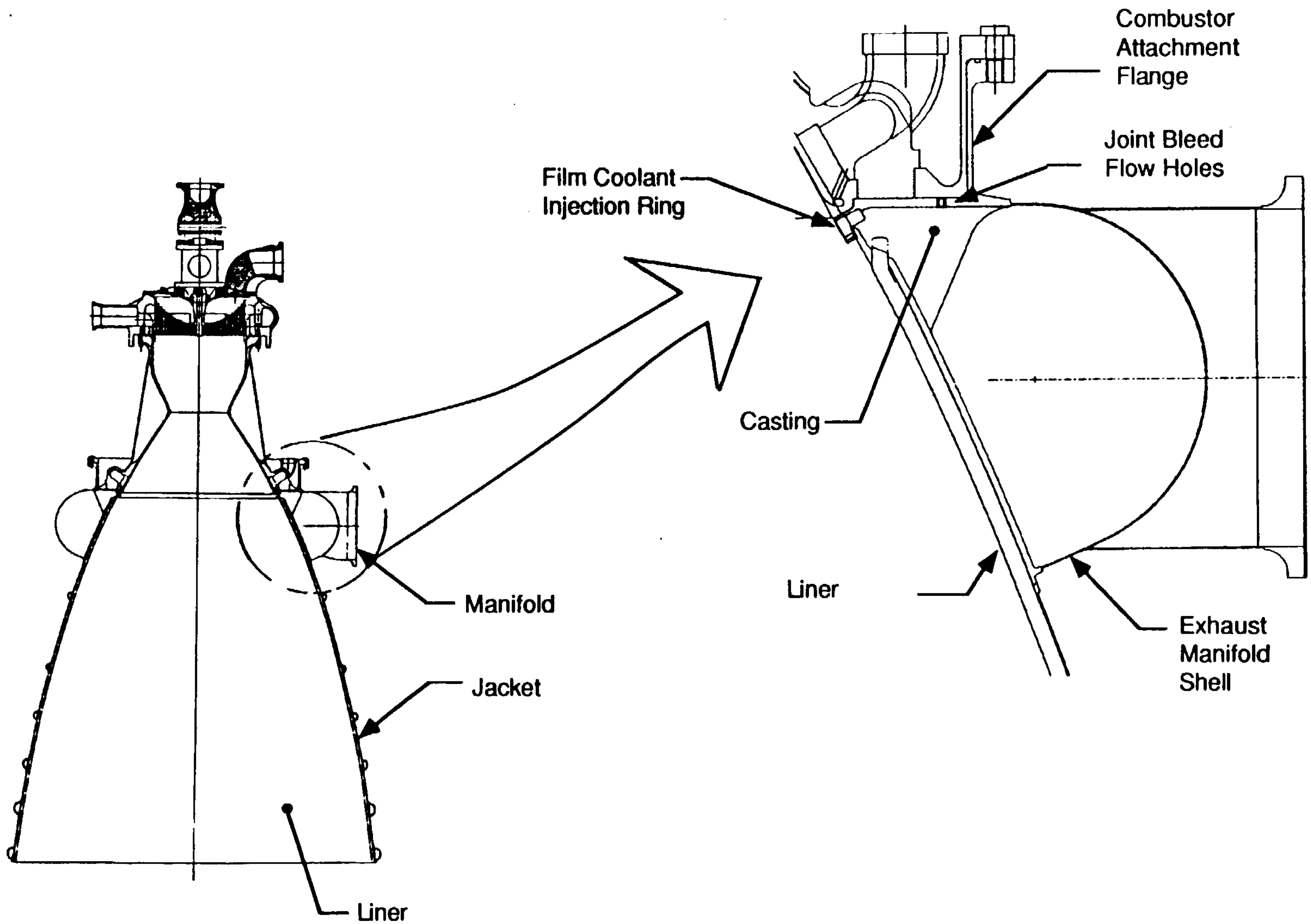
NOZZLE DESIGN



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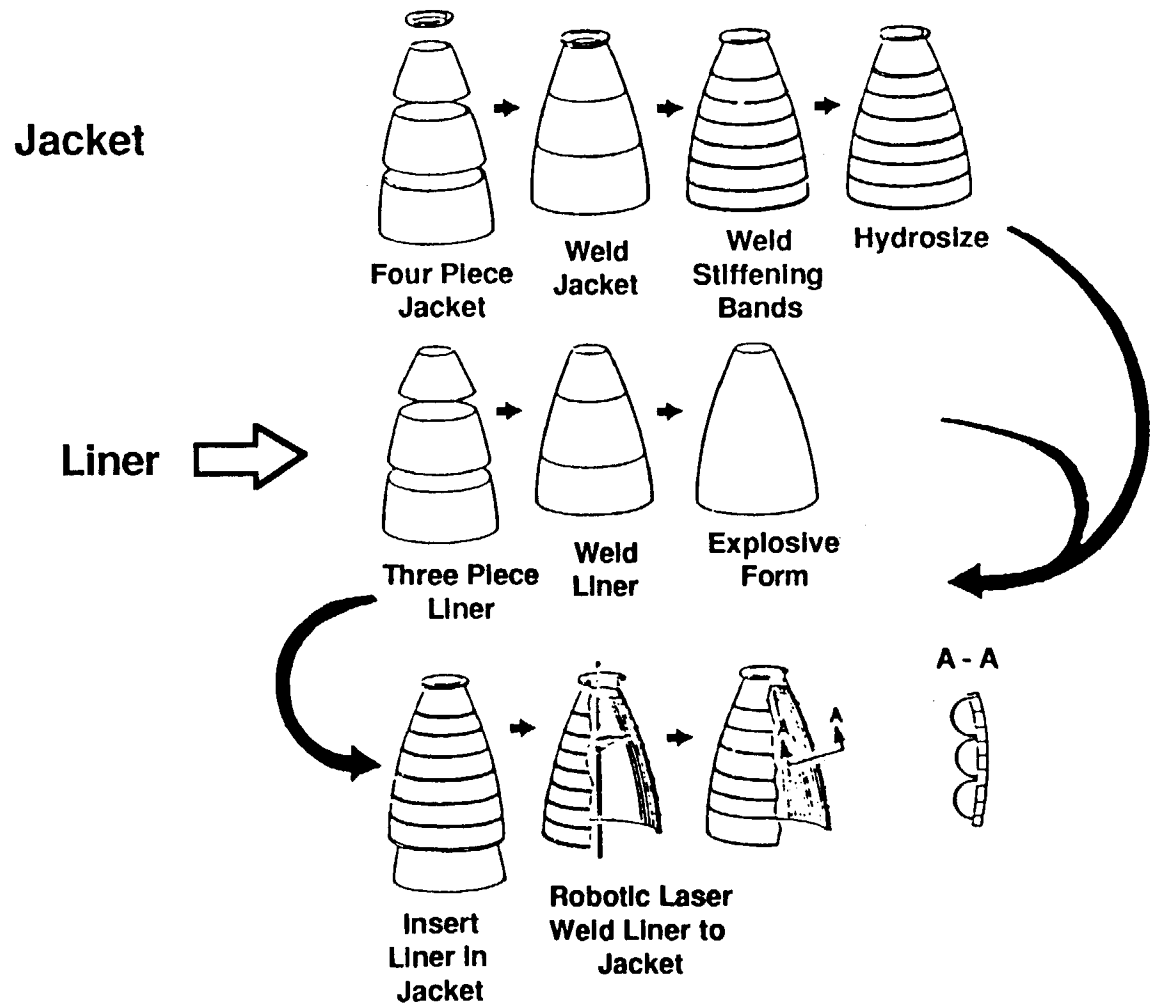
NOZZLE FABRICATION

Convoluted Passages - Fabrication Sequence



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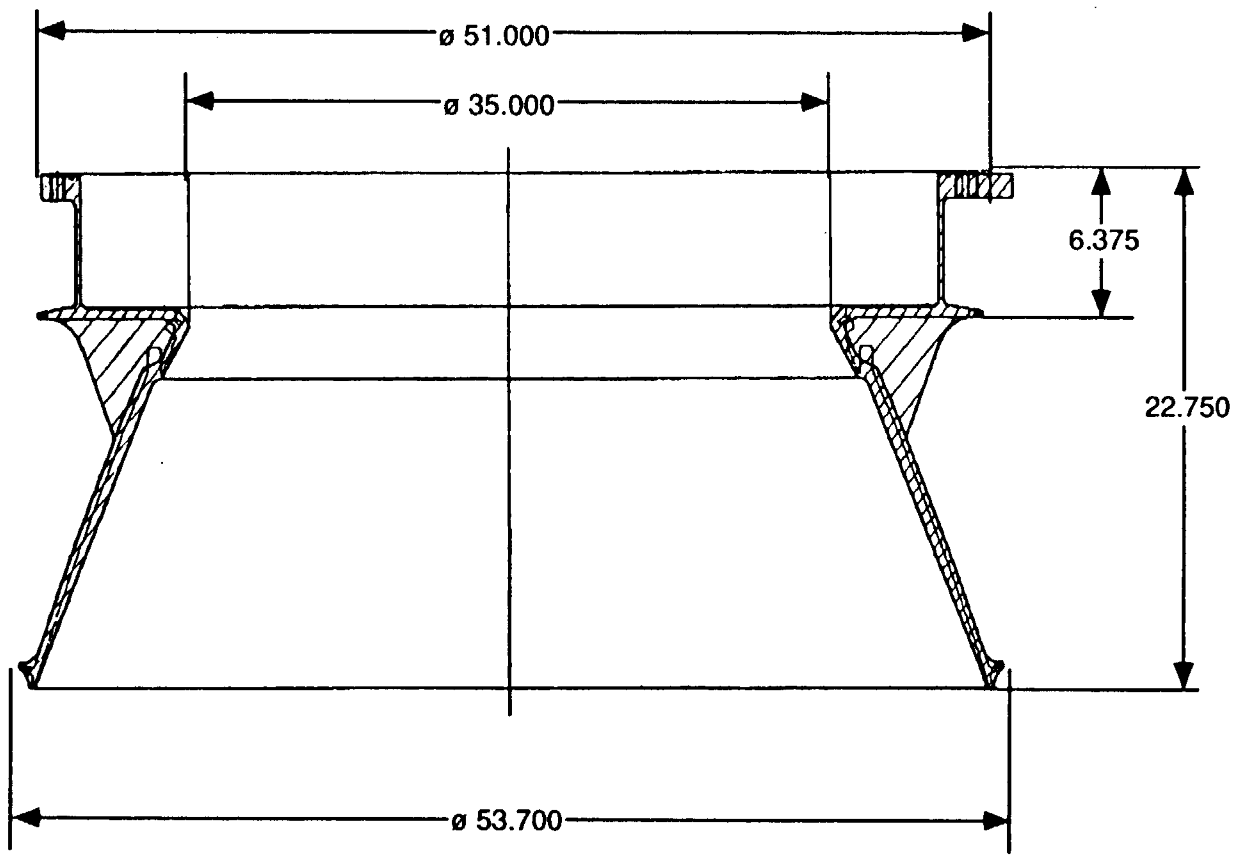
NOZZLE DESIGN EVOLUTION

- **Turbine exhaust manifold changed from full-torus to half-torus**
  - Lighter weight
- **Combustion chamber attachment flex ring added**
  - Solves joint thermal expansion delta
- **Liner made from one piece instead of three**
  - Lower cost
- **Convolutes of liner flattened**
  - Eliminates unknown thermal characteristic of intersticies of convolutes

FORWARD FLANGE CASTING DESIGN

- **INCO 625 selected for casting**
  - Provide thermal expansion compatibility with INCO 625 jacket
- **As poured weight = 950 lbs**
  Machined weight = 560 lbs
  - Total nozzle weight = 1600 lbs
- **Design to accommodate attachment schemes for various cooling methods**
  - HVS over tubes
  - Brazed tube
  - Laser welded convolute
- **Access for inspecting manifold weld joint**

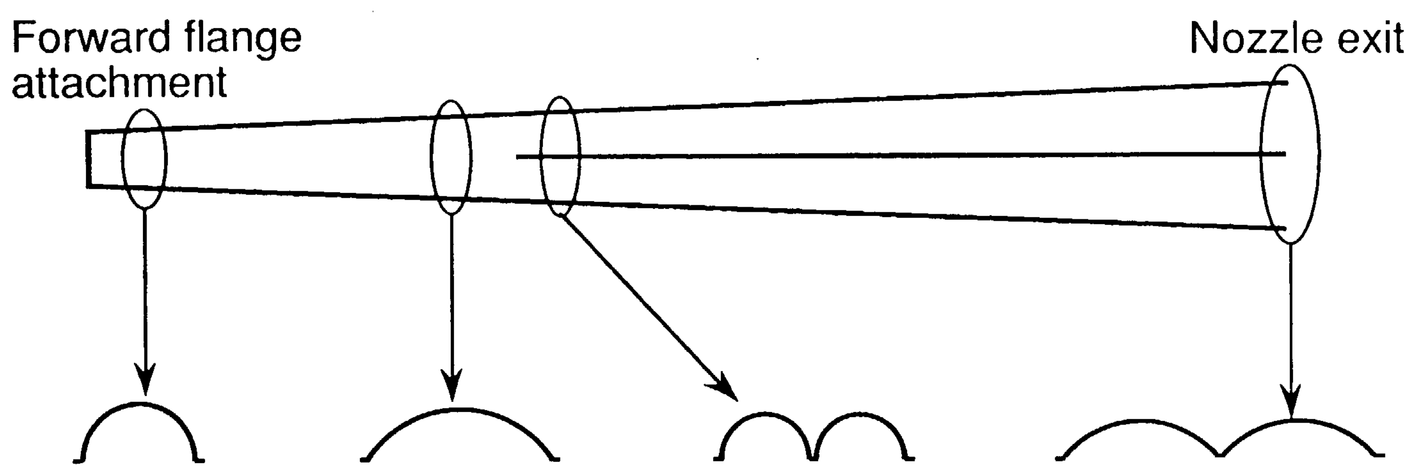
FORWARD FLANGE CASTING DESIGN



BASELINE CONVOLUTE LINER CONFIGURATION

90 convolutes at forward end

0.060" land between convolutes



Width	1.25	2.00	0.96	1.37
Height	0.63	0.54	0.48	0.39

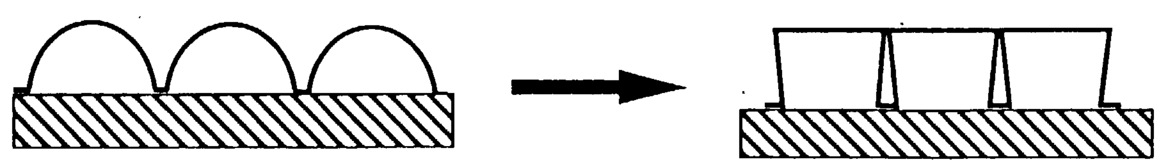
EXPLOSIVELY FORMED CONVOLUTE NOZZLE
Advantages

- **Explosively formed sheet metal successfully utilized in production**
  - SSME vacuum braze bag
  - ELV RS-27 thrust chamber bag (12:1 and 8:1)
- **The liner coolant passages are explosively formed in a die in one step**
- **Easily automatable process**
- **No braze alloy needed**
- **No tubes required**
- **Consistent geometry of coolant passages**
  - No spring back during explosive forming passages with 0.015" material thickness
- **Can make coolant passages in various shapes**
  - Not limited to circular passages
- **Explosive forming process is not sensitive to material selection**

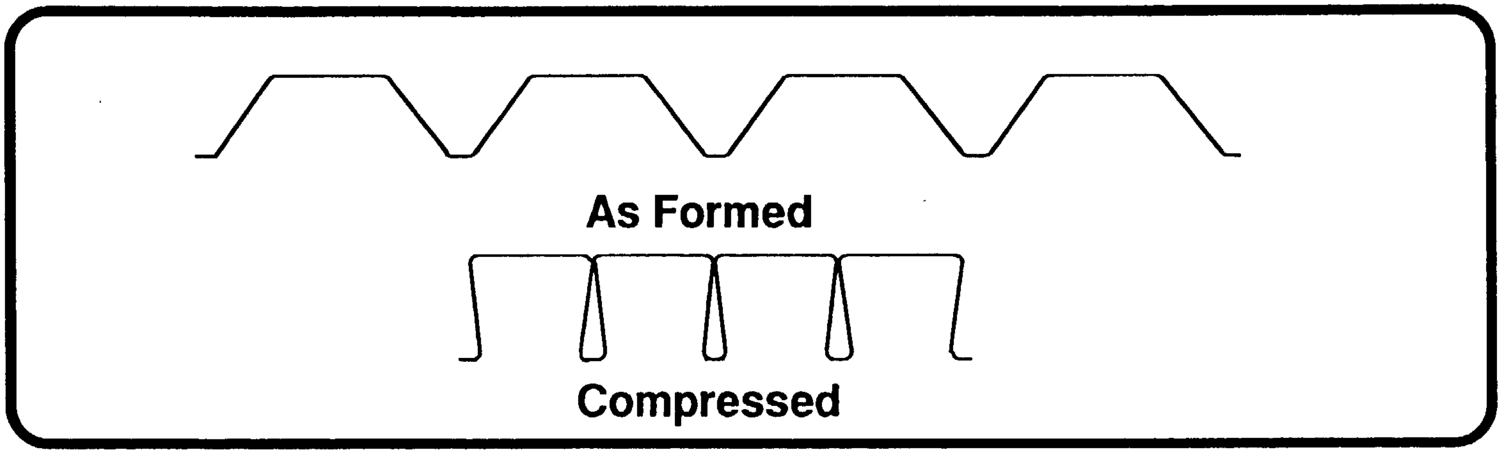
FILM COOLANT BEHAVIOR IN INTERSTICES UNKNOWN

- **Convolute configuration is outside of design experience for nozzles**
  - Major concern is film coolant behavior in interstices
  - Tube wall nozzle treated as flat plate for film cooling analysis

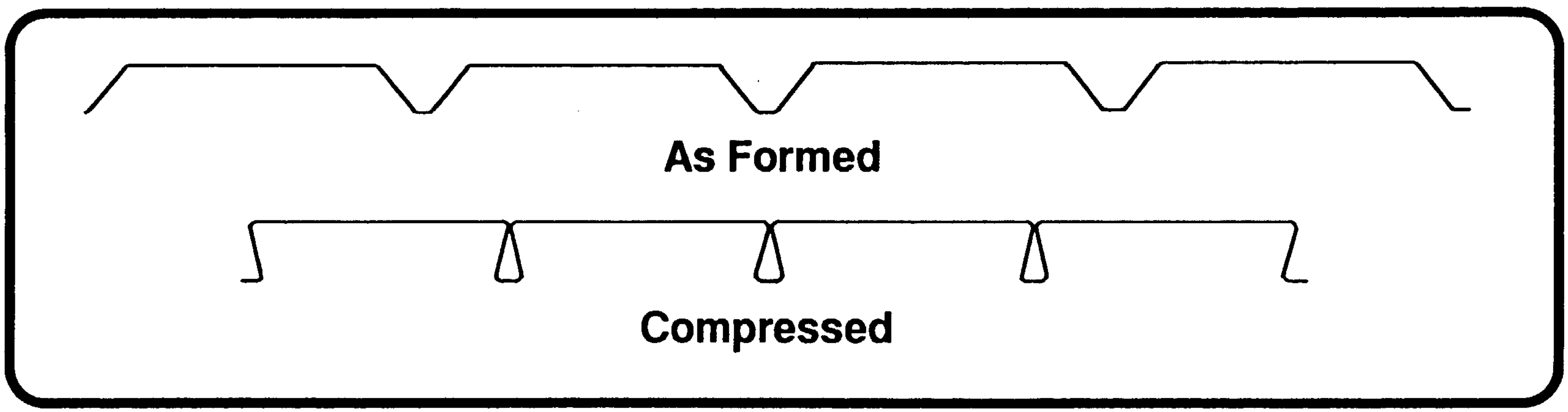
- **Convolute nozzle configuration evolved into a flat surface on the hot gas surface**
  - Film cooling analysis within experience



CONVOLUTE LINER IS COMPRESSED TO PROVIDE SMOOTH INNER WALL FOR NOZZLE



Cross-Section of Convolutes at Top of Liner

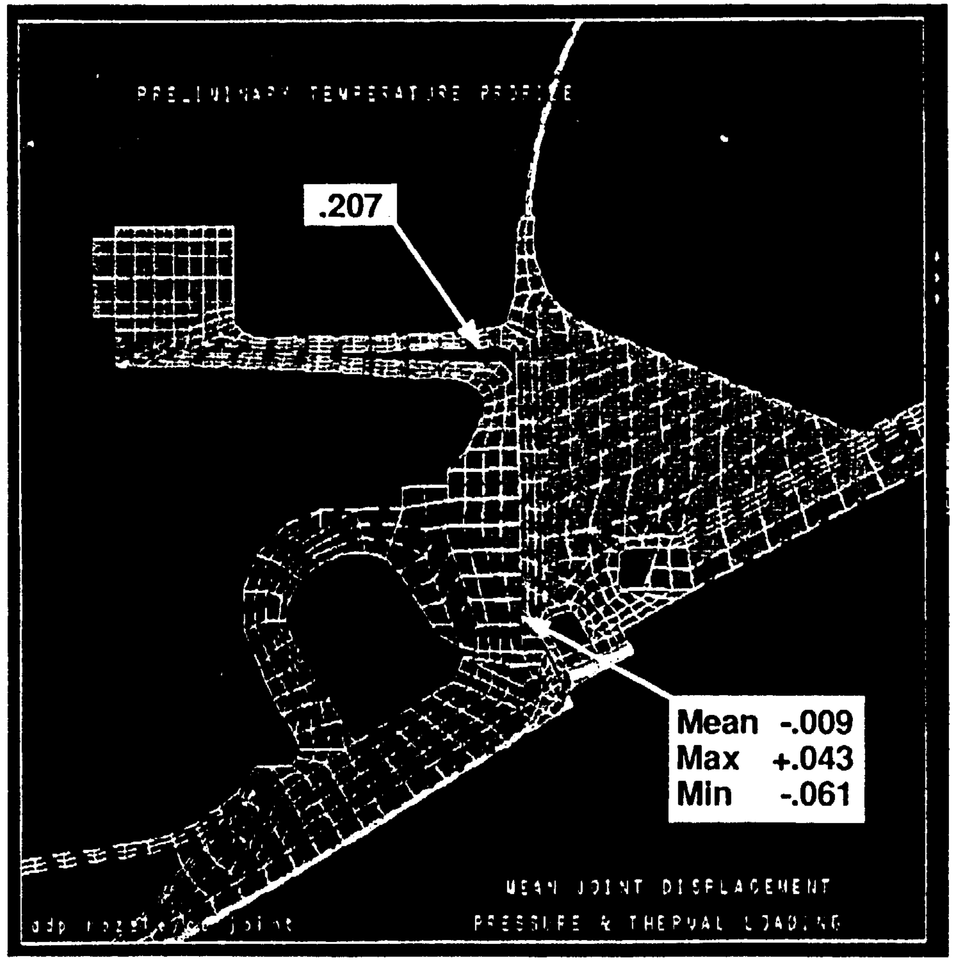


Cross-Section of Convolutes at Bottom of Liner

NOZZLE LOADING CONSIDERED

- **Side loading**
  - Random vibration (.007 G^2/Hz, 10-200 Hz)
    - SSME zone Q vibration criteria adjusted for Barrett criteria
  - Start up flame separation
  - Gimbaling
- **Axial load**
  - Random vibration + 10% pressure
  - Nozzle pressure load
- **Thermal load**

JOINT DISPLACEMENT PROFILE



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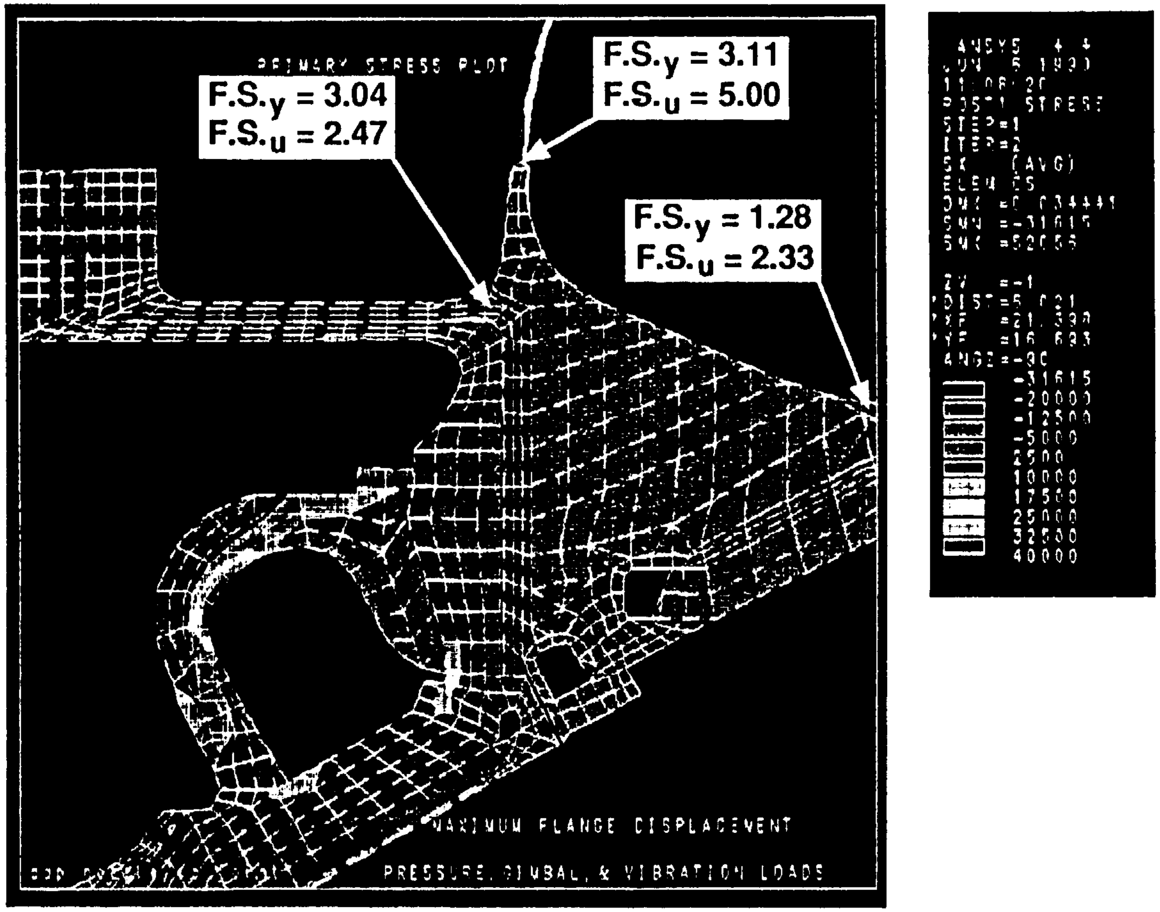
94LS/077-257

PRELIMINARY JOINT DISPLACEMENT ANALYSIS RESULTS

- **Radial mismatch on hot gas wall = 0.120"**
  - Shroud attachment deflects radially 0.207"
- **Axial displacements range from 0.061" interference to 0.043" gap**
  - Asymmetric displacement during start up and gimballing loads
- **Flow recirculation is prevented by bleed flow in cavity**
  - Open annulus machined in nozzle to chamber interface
  - Bleed flow from turbine exhaust gas manifold provides positive pressure to prevent combustion gases from entering cavity

JOINT STRESS PROFILE

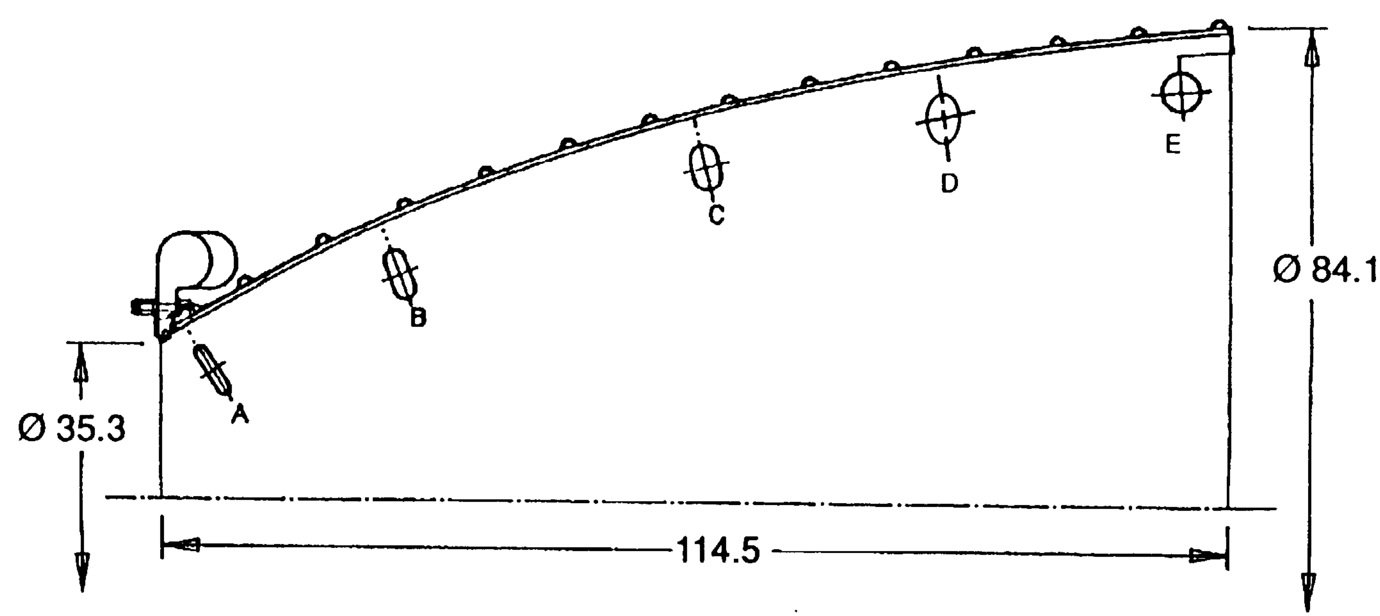


PRELIMINARY COMBUSTOR/NOZZLE JOINT ANALYSIS RESULTS

- **Temperature profile:**
  - $\Delta T = 0$ at the combustor/nozzle bolted flange interface
  - Low cost non-metallic seal effective at 250°F
  - Film cooling nozzle region exposed to 1340°F
    - Transpiration cooled wall
    - Bleed flow into the cavity
- **Displacement profile:**
  - At steady state the combustor/nozzle interface is closing
  - Asymmetric displacement during start-up and gimbaling only
  - Eliminate recirculation effects
    - Bleed flow into the cavity
- **Stress profile:**
  - Stresses are in allowable range

BASIC STRUCTURAL PARAMETERS

	Xi, in.	R, in.	Lt, in.	Primary Stress (psi)	F/S y	F/S ULT
A	20.3	.107	.42	784	>5.0	>5.0
B	40.0	.155	.26	1499	>5.0	>5.0
C	59.1	.190	.16	1863	>5.0	>5.0
D	84.4	.222	.057	1994	>5.0	>5.0
E	106.4	.242	.00	1836	>5.0	>5.0



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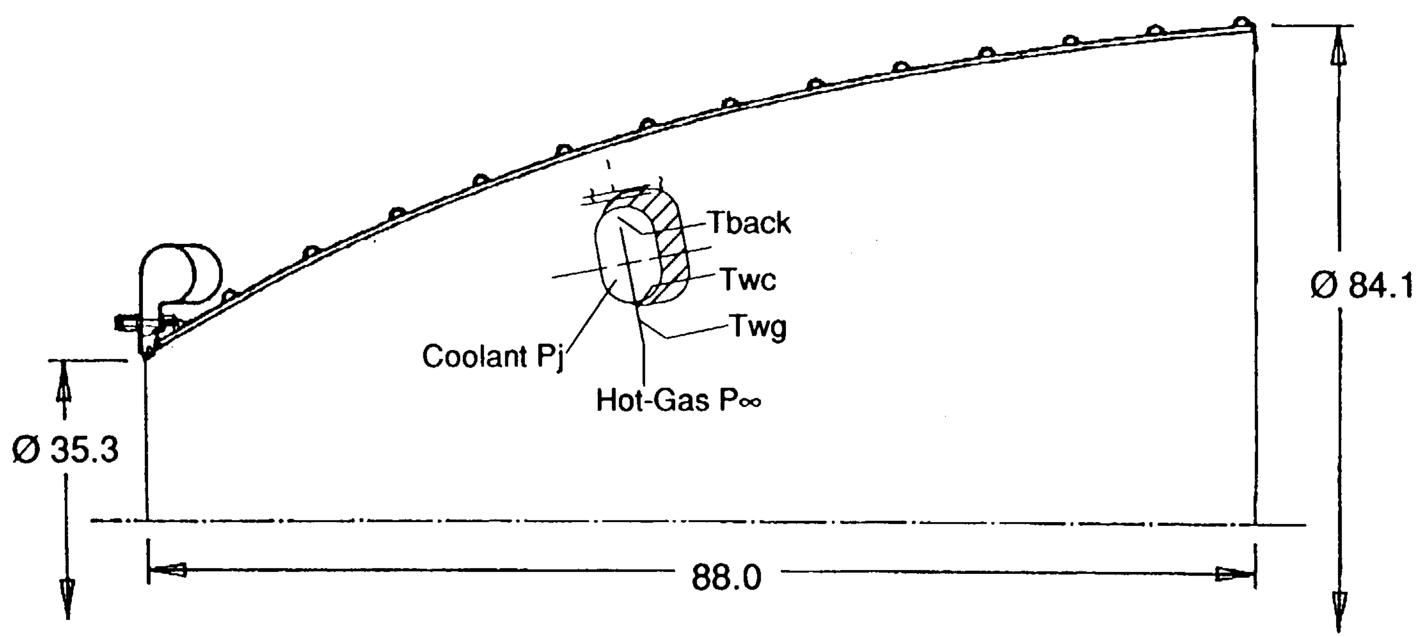
BASELINE THERMAL OPERATING CONDITIONS

	Xj, in.	Pj, psi	P∞, psi	Twg, °F	Twc, °F	Tback, °F
A	20.3	132.0	58.7	678	673	644
B	40.0	123.7	27.0	1308	1266	669
C	59.1	114.7	16.7	1640	1595	768
D	84.4	100.6	10.8	1621	1583	910
E	106.4	84.0	8.1	1598	1565	1025



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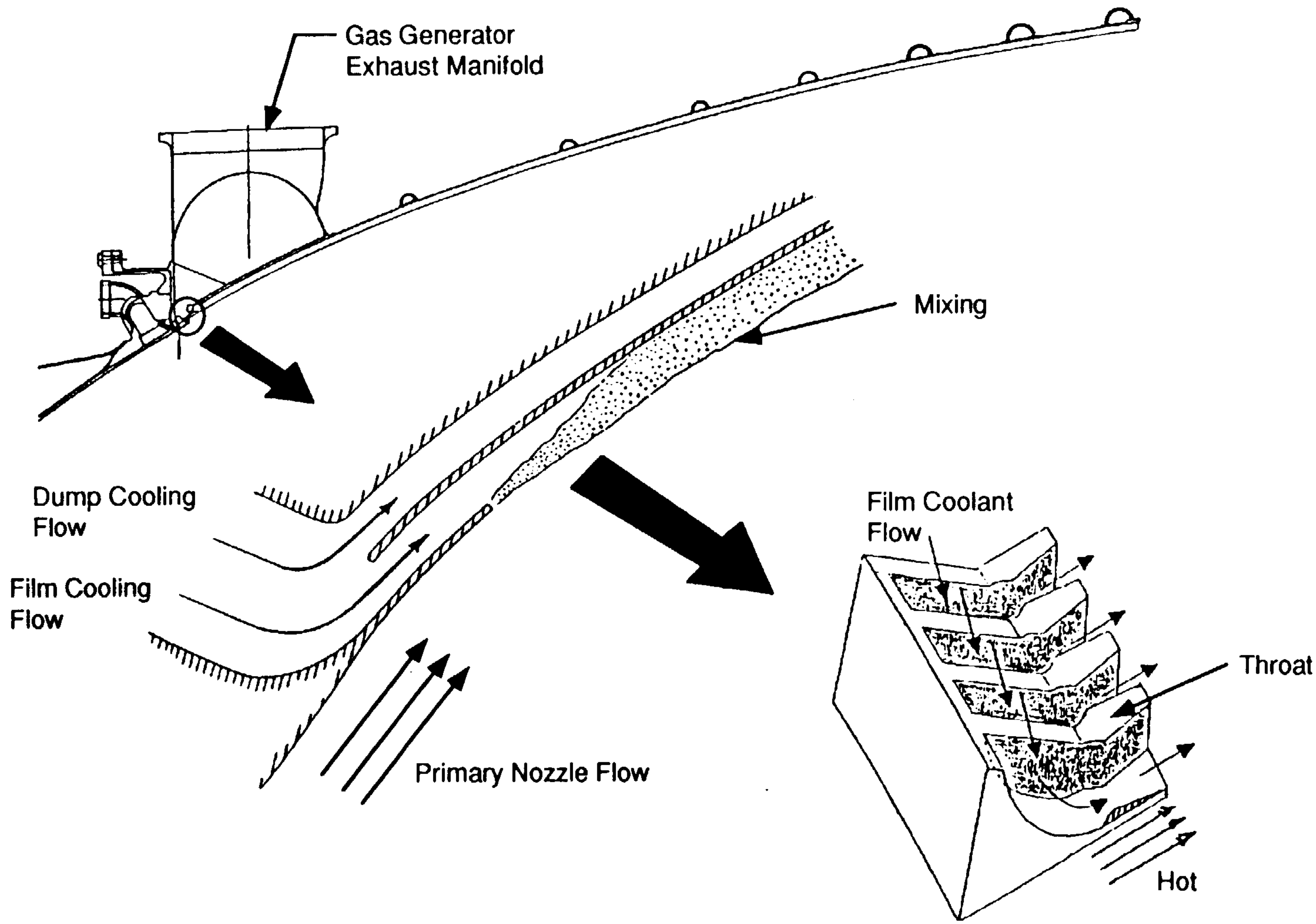
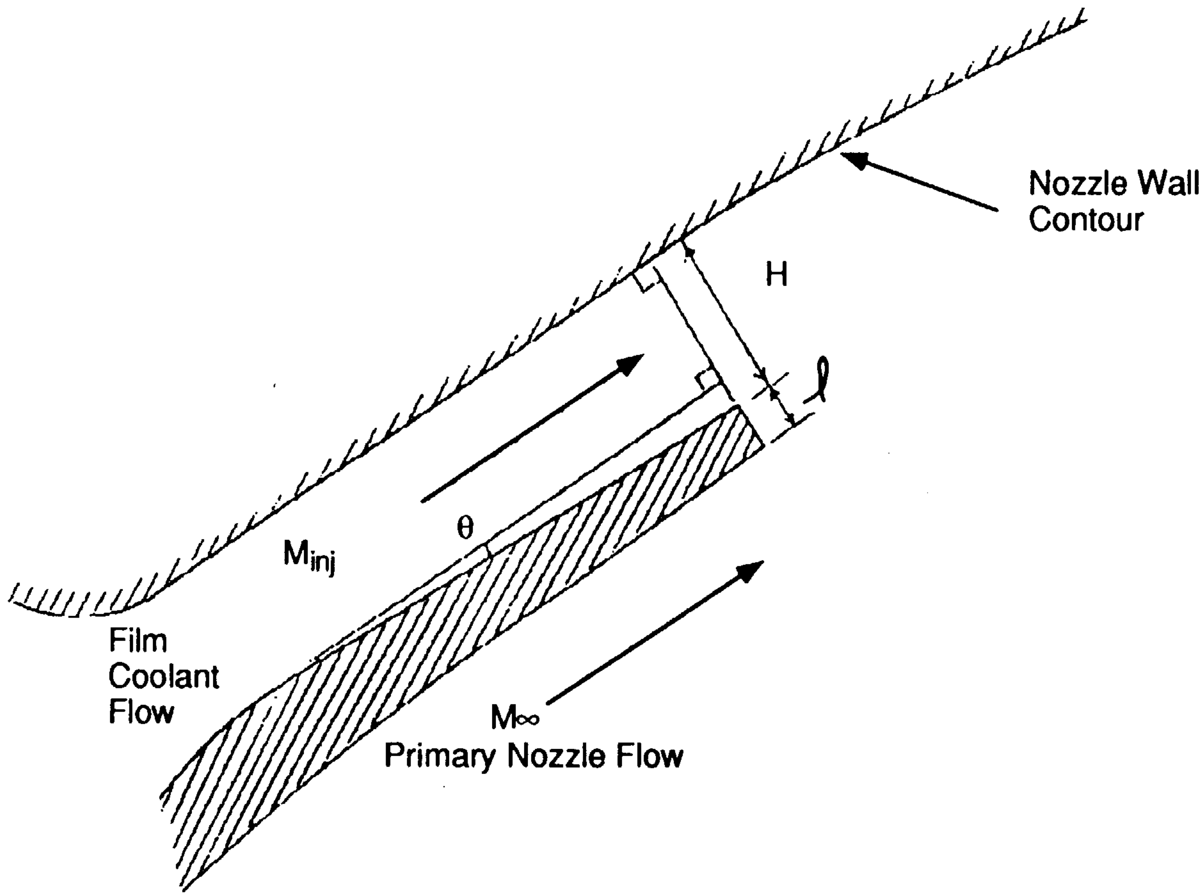
CONCLUSIONS

- **Updates on the baseline ADP nozzle contour wall:**
  - $\varepsilon_{exit} = 40:1$
  - Coolant passage material - Inconel 625
  - Maximum wall temperature - 1640°F
  - Nozzle coolant passage FTY S.F - >5.0
  - Nozzle coolant passage FTU S. F - >5.0
- **Thermal assessment on the nozzle off-design operating conditions indicated to be satisfactory with current GG coolant supply pressure of 150 psia**

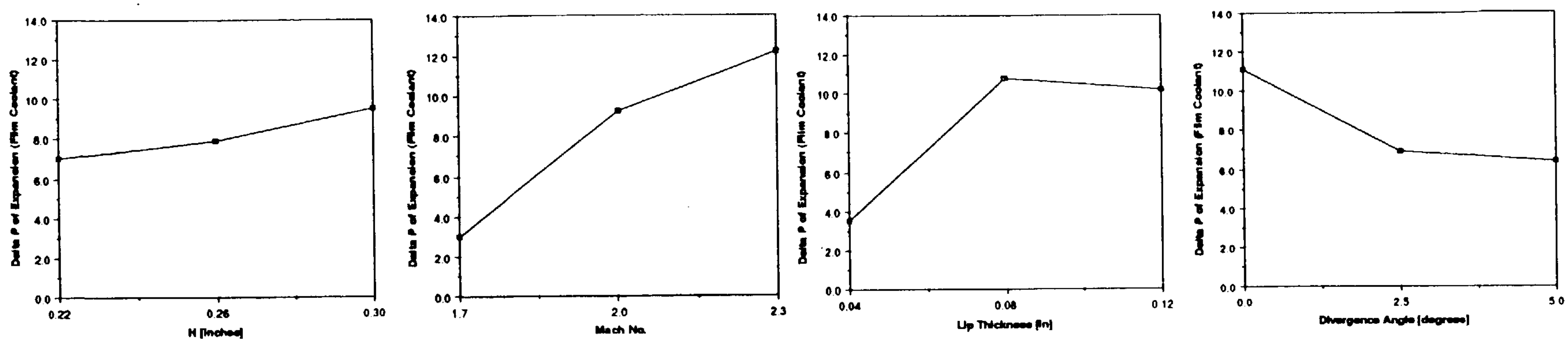
SCHEMATIC OF GAS TURBINE EXHAUST FILM COOLING CONCEPT



SCHEMATIC OF WATER TABLE TEST MODEL GEOMETRY

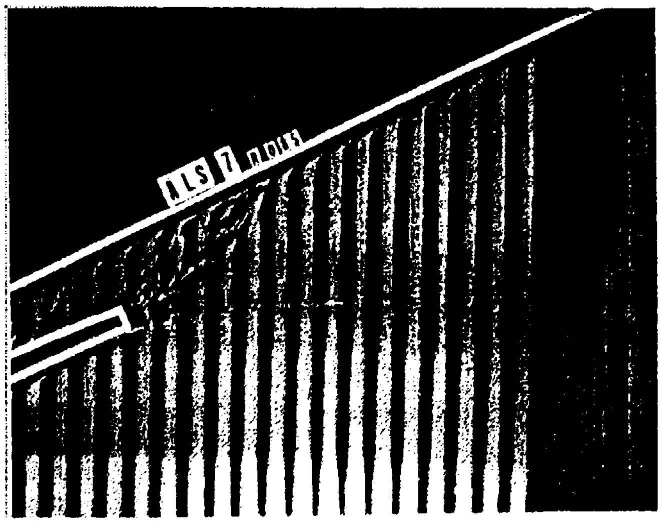


PARAMETRIC RESULTS FROM WATER TABLE STUDY OF FILM COOLANT INJECTION GEOMETRY

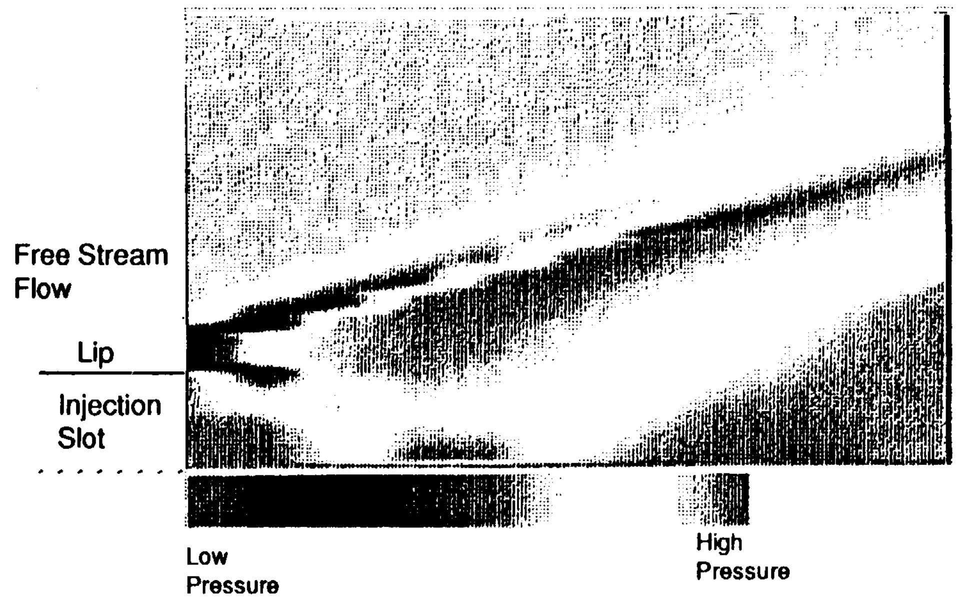


- **Injection flow trends observed from parametric study:**
  - Increasing the slot height, H, results in a thicker coolant layer - improved cooling
  - Increasing Mach number makes coolant layer more resistant to perturbation
  - Thinner lip is better — less transverse momentum flux to be reconciled
  - Parallel injection best
  - CFD predicts minor reduction in cooling effectiveness due to film divergence, but primary flow field characteristics are unchanged by this parameter
- **Within realm of interest, flow parameters do not result in major flow interference effects**
- **Pressure field at injection works to match local flow conditions**
- **Physical phenomena observed in water table simulations agree with computational results**

COMPARISON OF INJECTION ZONE PRESSURE FIELD PREDICTION FROM WATER TABLE AND COMPUTATIONAL STUDIES



Water Table Injection Simulation



SHIP CFD Injection Simulation

PRELIMINARY TAGUCHI STUDIES DESIGNED TO IDENTIFY KEY PARAMETERS

L8 Taguchi to study supersonic coolant injection

- Film coolant stagnation pressure
- Area ratio of injection
- Film coolant stagnation temperatuare
- Film coolant mixture ratio
- Film coolant nozzle lip thickness
- Film coolant injection pressure ratio
- Film coolant mass flow rate

L9 Taguchi to study subsonic coolant injection

- Film coolant injection mach number
- Area ratio of injection
- Film coolant mass flow rate
- Film coolant mixture ratio

Studies included many control parameters to determine which were primary factors

CONCLUSIONS DRAWN FROM FILM COOLING ANALYSIS

- Injection at matched pressure is optimal for a given mass flow rate

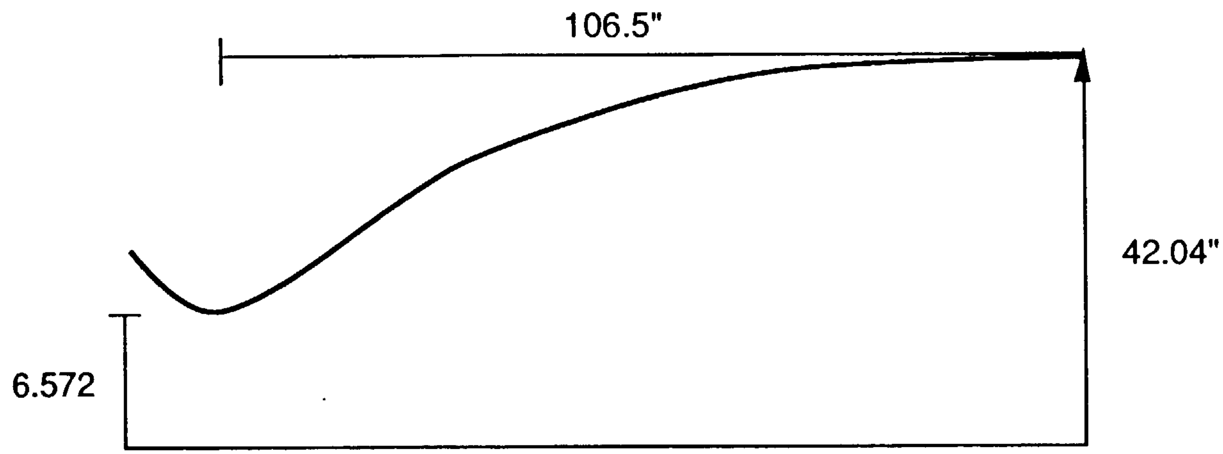
- Bulk properties of the film coolant (film coolant flow rate, temperature and momentum) have the greatest impact upon film cooling performance. Optimization of local injection features such as lip thickness and exit pressure ratio yield comparatively minor increases in performance

- Baselined film coolant injection pattern provides uniform film coverage

- Thin lip best, but lip thickness has a minimal effect on overall film cooling performance. Choice of lip thickness can be based on local aerothermal and structural considerations.

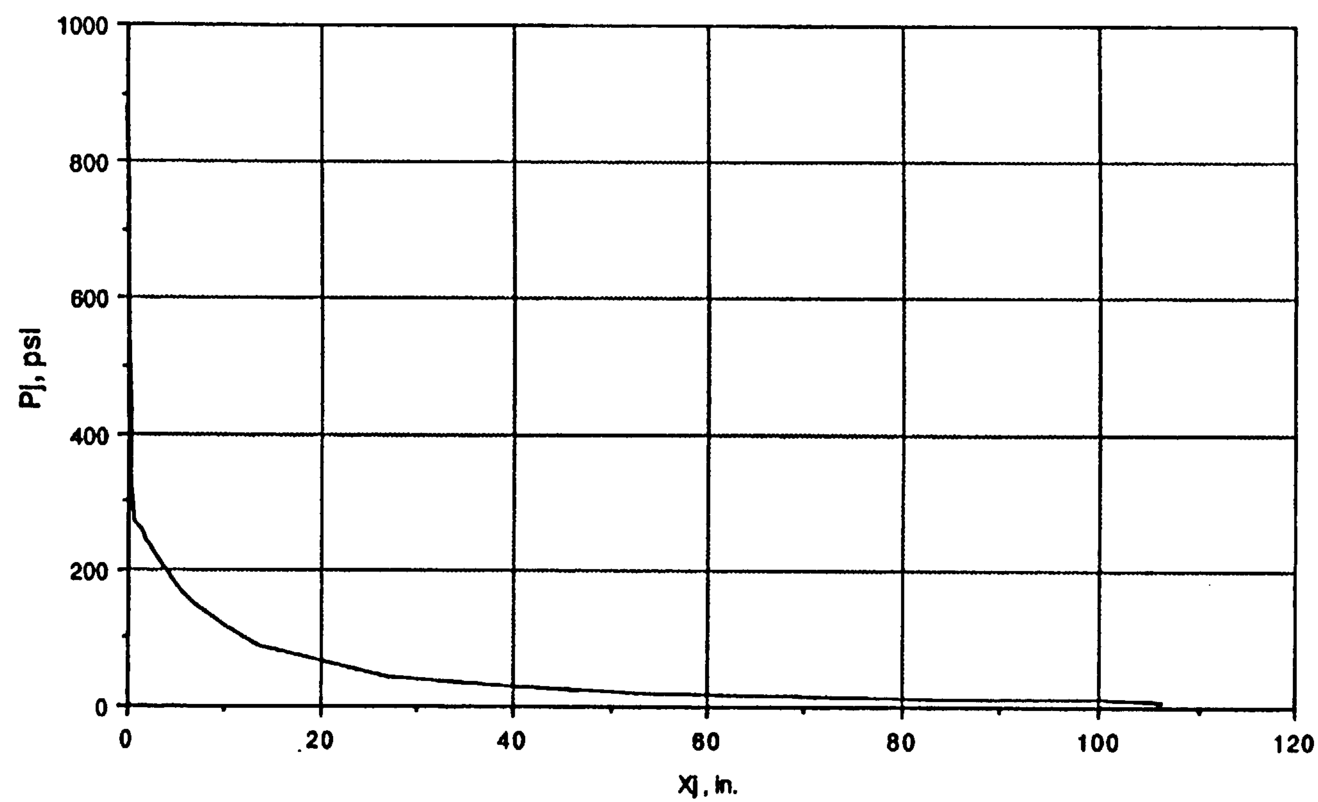
- The effects of interaction of the injection parameters with each other are minimal

NOZZLE CONTOUR WALL

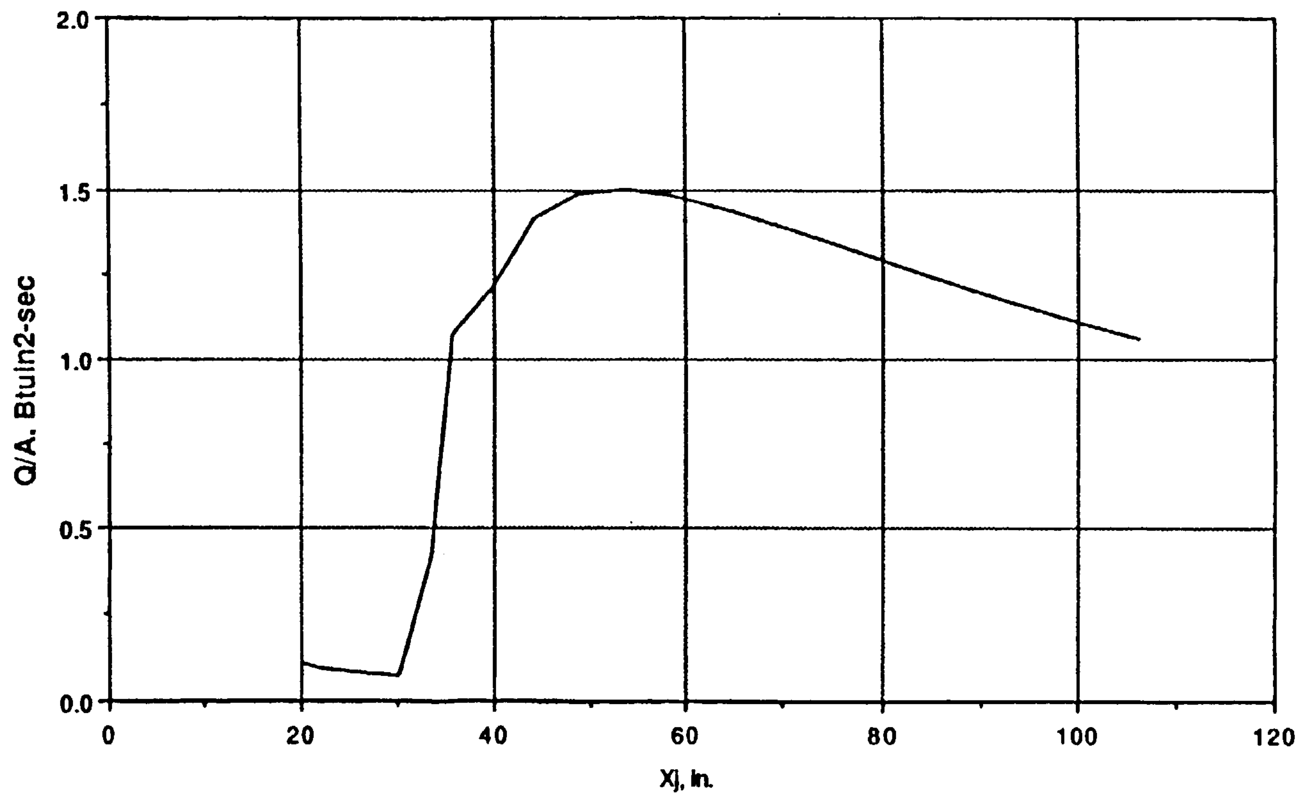


- **80% length RAO contour wall**
  - Maximum expansion angle 33.36
  - Exit plane wall angle 7.5°
  - Exit area ratio 40:1

NOZZLE
Pressure Profile



NOZZLE
Heat Flux (with film cooling) Profile



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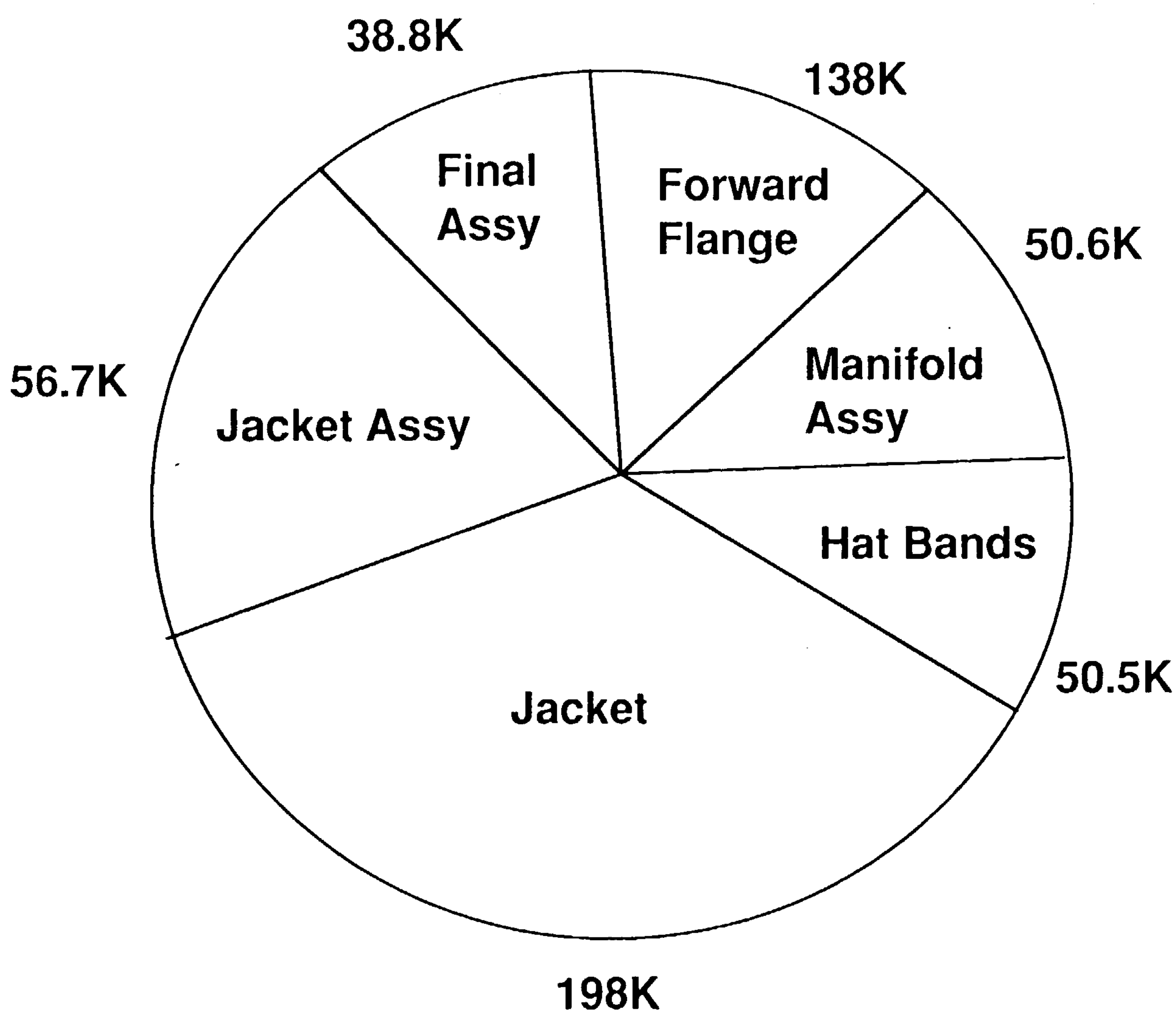
CONVOLUTE NOZZLE COST BREAKDOWN
September 1990

500th Unit Cost
50/year, 1990 $



Total = $532,600

2.4.3 HYPERVELOCITY SPRAYED (HVS) NICKEL ALLOY 625

TASK OBJECTIVE AND GOALS FOR MATERIAL PROPERTIES

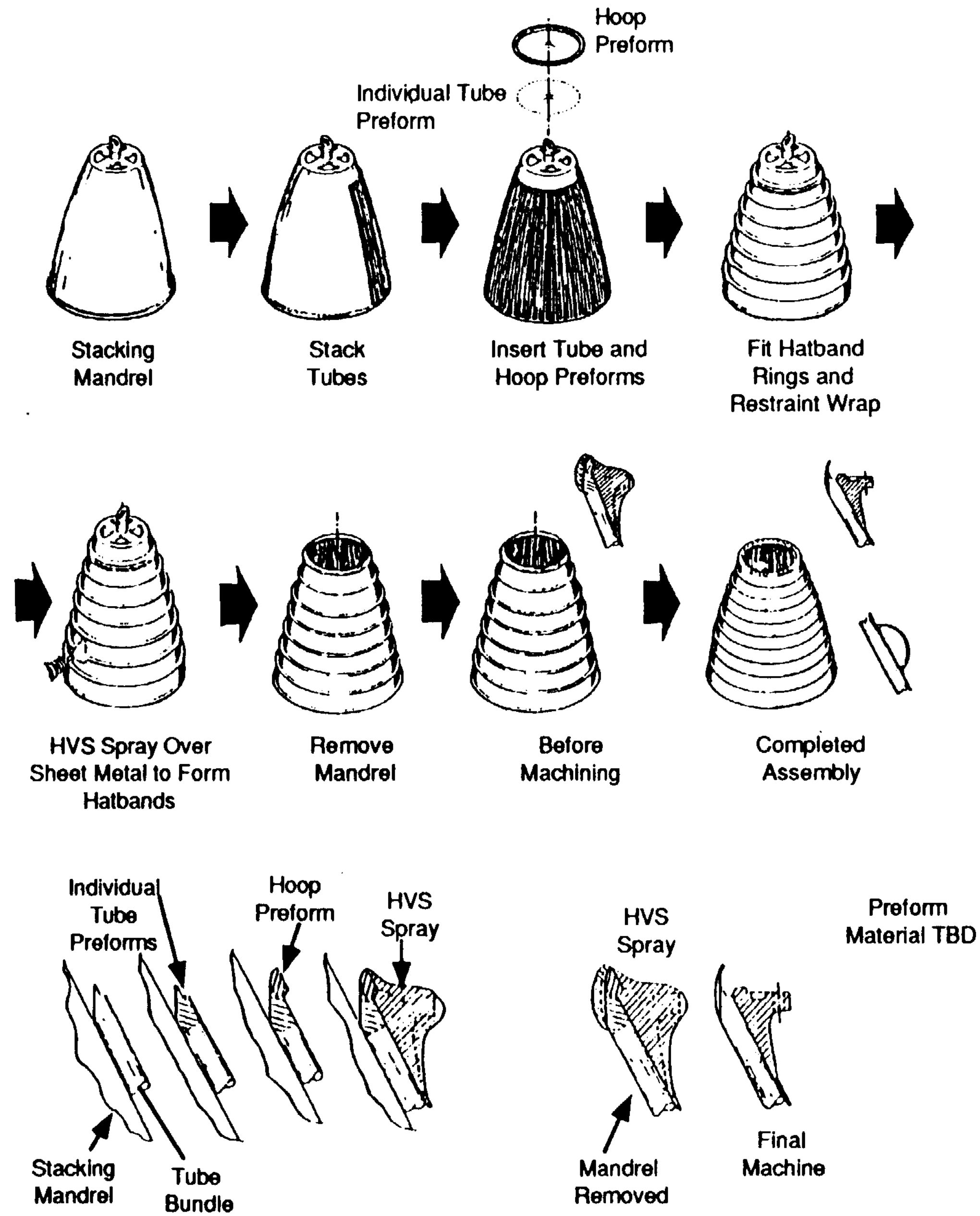
- **Task Objective:** To develop a low cost spray forming method for nozzle fabrication

- **Materials properties goals for as-sprayed Alloy 625**

• Ultimate strength	106 ksi	(80% of wrought*)
• Yield strength	54 ksi	(80% of wrought)
• Elongation	32%	(80% of wrought)
• Elongation at 1250°F	12%	

* Wrought properties based on conventional, annealed Alloy 625 expected minimum values from Rocketdyne Materials Property Handbook adjusted to typical

HVS NOZZLE FABRICATION APPROACH



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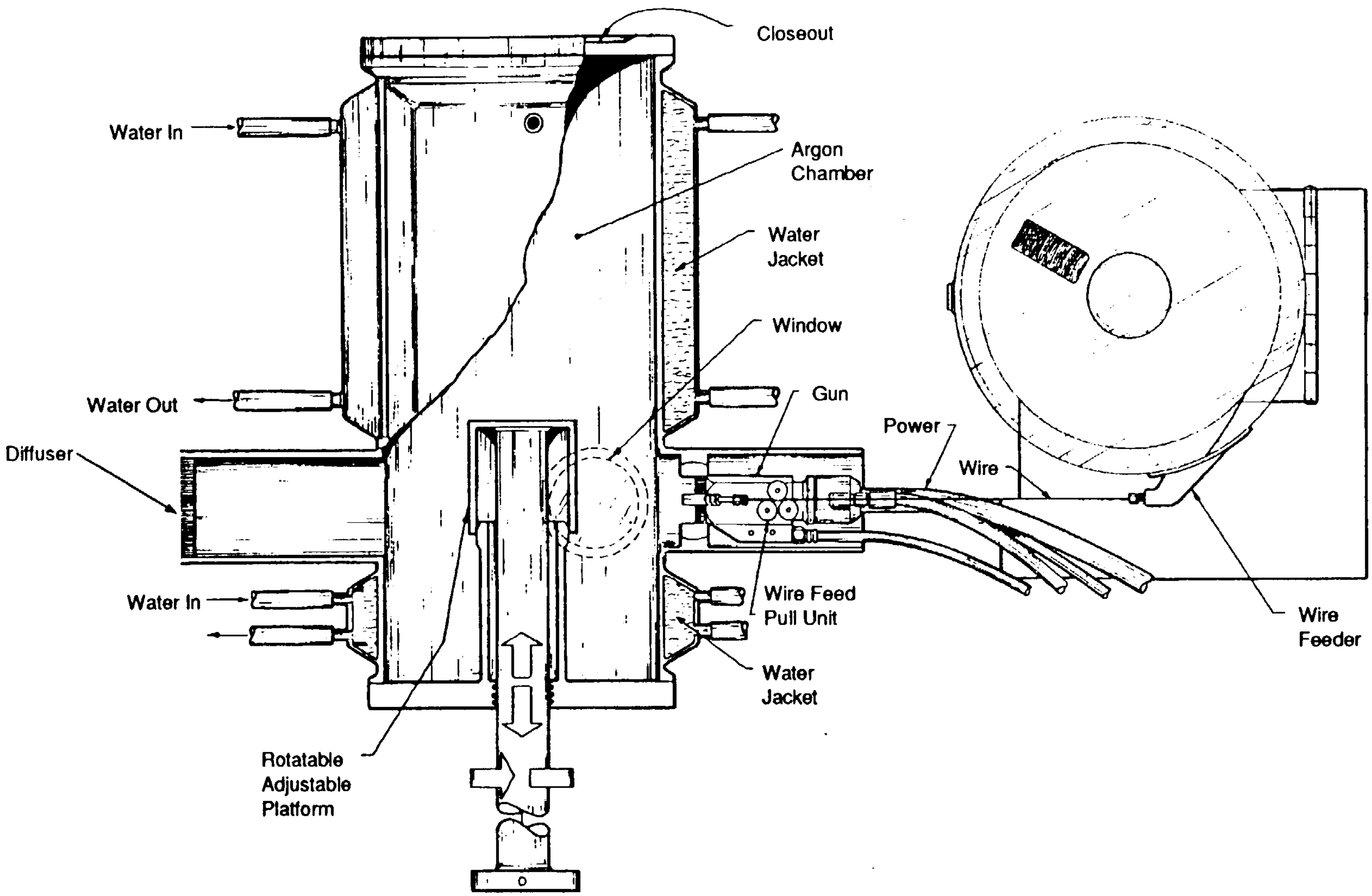
HYPERVELOCITY SPRAY SYSTEM AT OREGON GRADUATE INSTITUTE



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APPROACH TO ACHIEVE ACCEPTABLE HVS MATERIAL PROPERTIES
December 1989

- **Background - IR&D HVOF Alloy 718 Task - FY '89 and '90**
  - Sprayed in air
  - Poor as-sprayed properties
  - Acceptable heat treated ductility
  - Relatively cool substrate
  - Low deposition rate

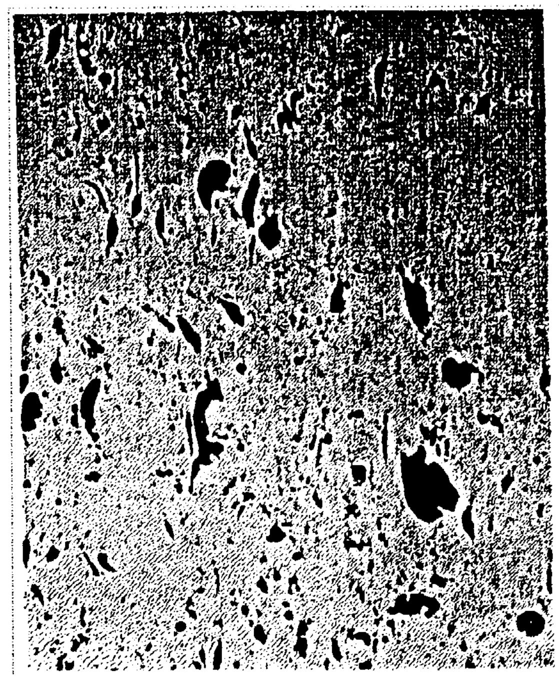
Approach	Result
• Use higher deposition rate HVOF gun at Leeman Ferry Facility. Shroud substrate with an inert gas.	• Very poor as-sprayed and heat treated properties
• Use high deposition rate HVS gun at Oregon Graduate Institute. Shroud substrate within inert gas.	• Poor properties
• Use high deposition rate HVS gun at Oregon Graduate Institute. Place substrate in an inert chamber.	• Excellent properties

PROGRESS IN IMPROVING HVS

Unetched 200X

Plazjet Sprayed 718

Sprayed at Vanderstratton from wire, August 1989

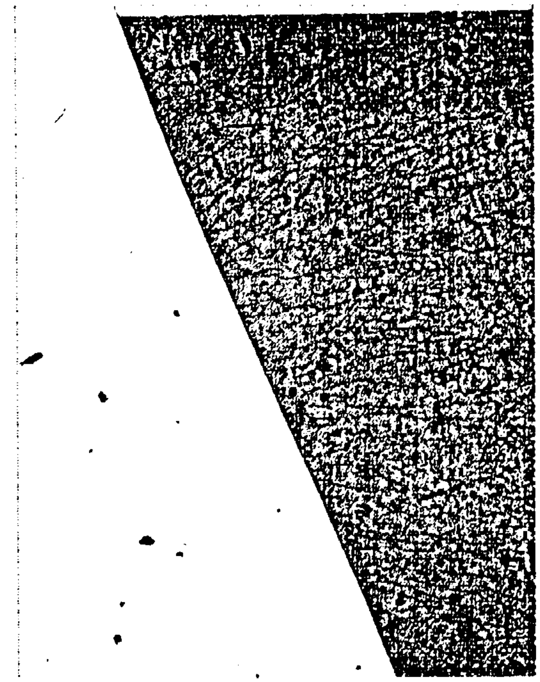


Unetched 200X

Plazjet Sprayed INCO 625

Sprayed at Oregon Graduate Institute, March 1990

Etched with electrolitic CrO3



Unetched 200X

Plazjet Sprayed 625

Sprayed at Oregon Graduate Institute, May 1990

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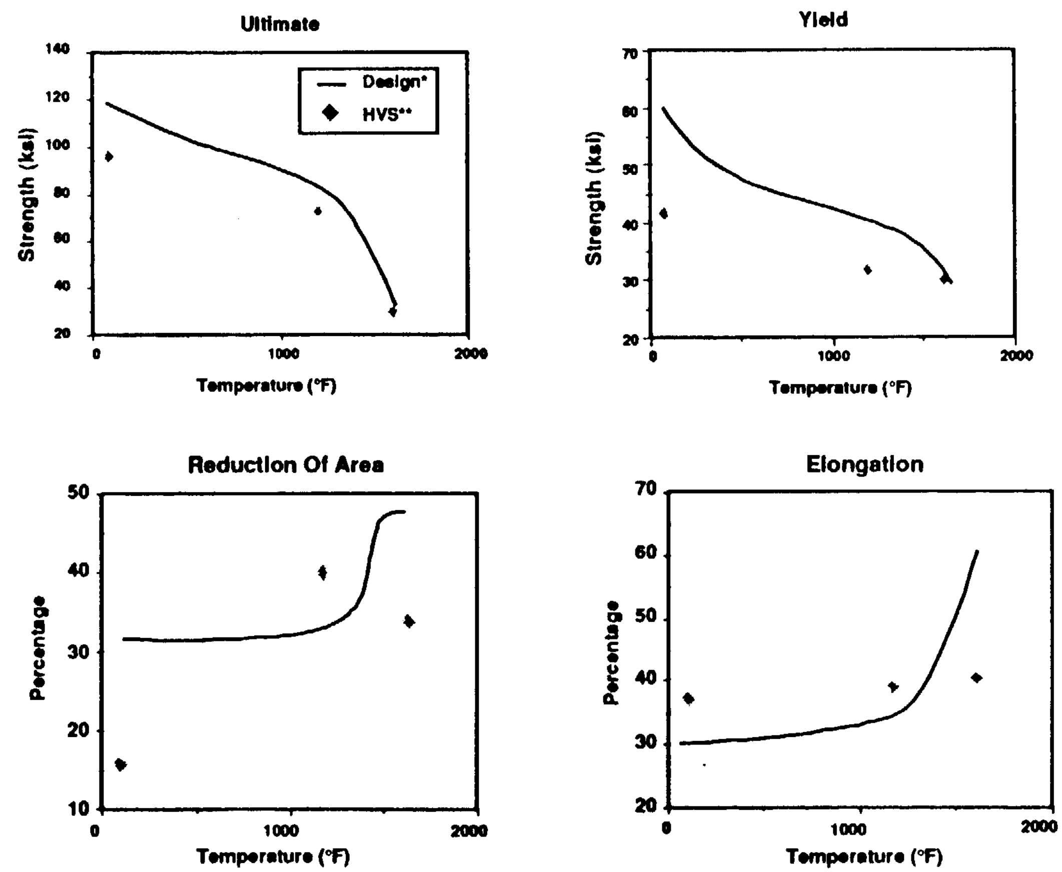
COMPARISON OF WROUGHT AND AS-SPRAYED ALLOY 625 MATERIAL PROPERTIES
June 1990



* Expected minimum values for Wrought Conventional, Annealed Alloy 625 from Rocketdyne Material Property Handbook

** Average of 4 tests per temperature

TUBE BUNDLE SUCCESSFULLY SPRAYED WITH HVS INCO 625

Rockwell International
Rocketdyne Division

SC90c-30-54
1XG91-7/23/90-01B* (M968)

HVS DEVELOPMENT TESTS REQUIRED TO RESOLVE TECHNICAL CONCERNS

Technical Concern	Development Test
Substrate temperature	Determine minimum acceptable substrate temperature
Bond integrity	Testing of tubes sprayed with HVS
Spray angle of gun relative to tubes	HVS samples at various angles to determine acceptable range
Deposit integrity in tube interstices	HVS specified tube-to-tube gaps and different tube crown configurations to determine deposit quality
Deposit characteristics on hatbands	Select and HVS hatband configuration to assess deposit quality
Deposit behavior when spray is interrupted and restarted	Investigate effects of starting and stopping on deposit characteristics

HVS DEVELOPMENT TESTS REQUIRED TO RESOLVE TECHNICAL CONCERNS

(Continued)

Technical Concern	Development Test
Distortion of tubes during spraying	Spray long tube samples to determine optimum bundle configuration
Determination of HVS thickness	Select and evaluate thickness measuring devices to verify HVS deposits
Behavior of HVS during hot fire testing	Fabricate and hot fire test subscale nozzle
Integrity of nozzle to manifold attachment	Assemble a segment of a manifold over tubes and spray to determine behavior of assembly
Environment for the full-size nozzle facility	Define HVS and nozzle temperature, determine heat radiation to walls of development facility, determine environment for hardware inside chamber

HVS DEVELOPMENT FOR ALS NOZZLE
ROM Cost Summary

● **Development Cost**	
• Facility	$500K
• Development	$500K
● **Material property characterization**	$300K
● **Full-size facility cost**	$2,250K
TOTAL	**$3,550K**

- **21 months from development start to full size facility completion**

COST OF HVS DEVELOPMENT AND FACILITIES FOR FULL SIZE NOZZLE

Too Expensive For ADP Program

- Initial IR&D data indicated HVS with shroud may produce acceptable material
- Early HVS results indicated an inert, ambient pressure chamber was required
- Technical concerns identified during HVS spraying at Oregon Graduate Institute
- Cooling system for ambient pressure inert chamber for full size nozzle required to dissipate heat from HVS process
- HVS deleted as candidate fabrication process for ADP nozzle

2.4.4 NOZZLE RESULTS

- Nozzle concept selection completed
- Film cooling taguchi analysis completed
- Film cooling water table testing conducted
- Preliminary design and analysis of nozzle components
- High velocity spray (HVS) samples completed and analyzed
- Nozzle summary report completed

2.5 IGNITION SYSTEM

The SSME and J-2 engines utilized a spark-torch ignition system (ASI). Review of the operational history revealed these systems to be highly reliable over a wide range of operating conditions. Although these systems worked well, costs for them were relatively high. To reduce the ignition system costs, new ignition technologies were reviewed as well as ways to make an ASI system less expensive.

Nine concepts were reviewed including a promising laser ignition system. The laser system had the potential to reduce costs but the technology was relatively new and unproven. In the end an ASI system was selected based on its proven track record and minimal development required. Development time was an important factor due to the short program schedule. However, the costs could be reduced in the system by separating the exciter electronics form the spark plugs which would reduce part complexity and simplify manufacturing flow. The internal geometry of the torch system duplicated the geometry used on the SSME engine to ensure the same ignition characteristics. The system was also designed to be common between the main injector and the gas generator, which would further reduce costs.

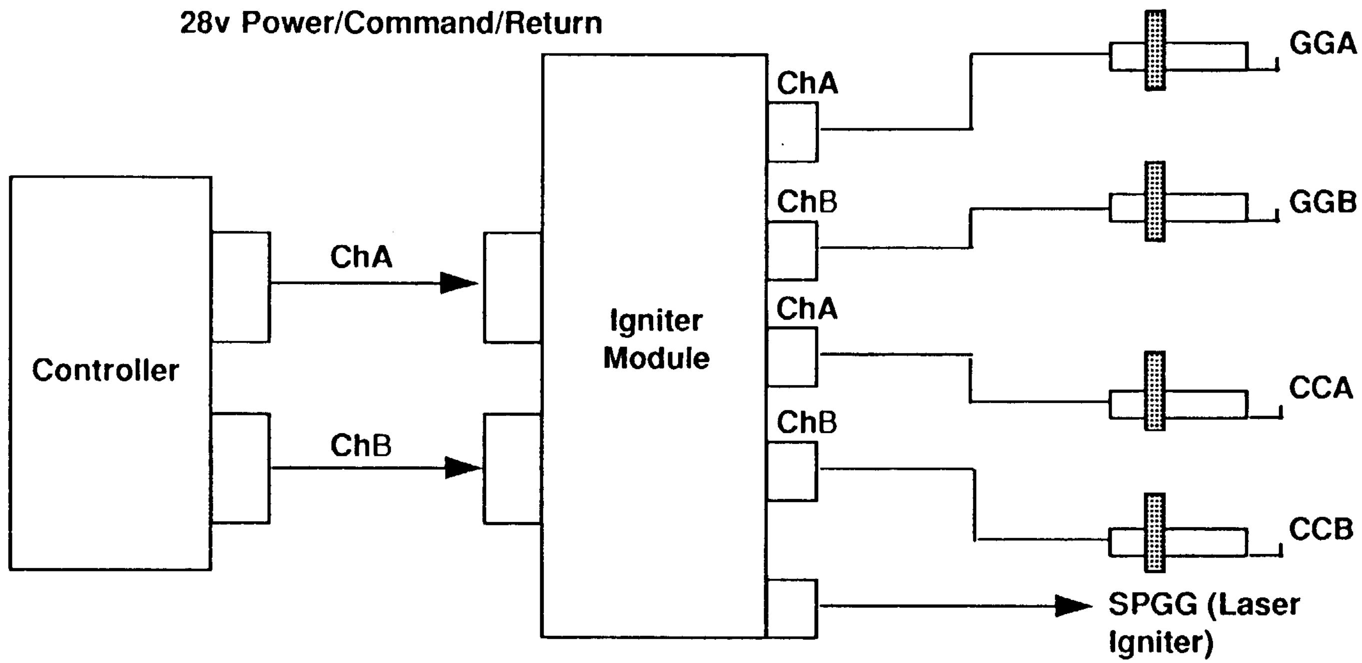
The charts that follow describe in detail the work associated with the ignition system design effort.

2.5 IGNITION SYSTEM

IGNITER MODULE

- **Features**
  - Igniter circuitry for gas generator and combustion chamber
  - Redundant channels for each combustor
  - Modified aircraft inductive discharge system
- **Functions**
  - Process commands from state controller
  - Initiate/terminate ignition spark

Igniter System Block Diagram



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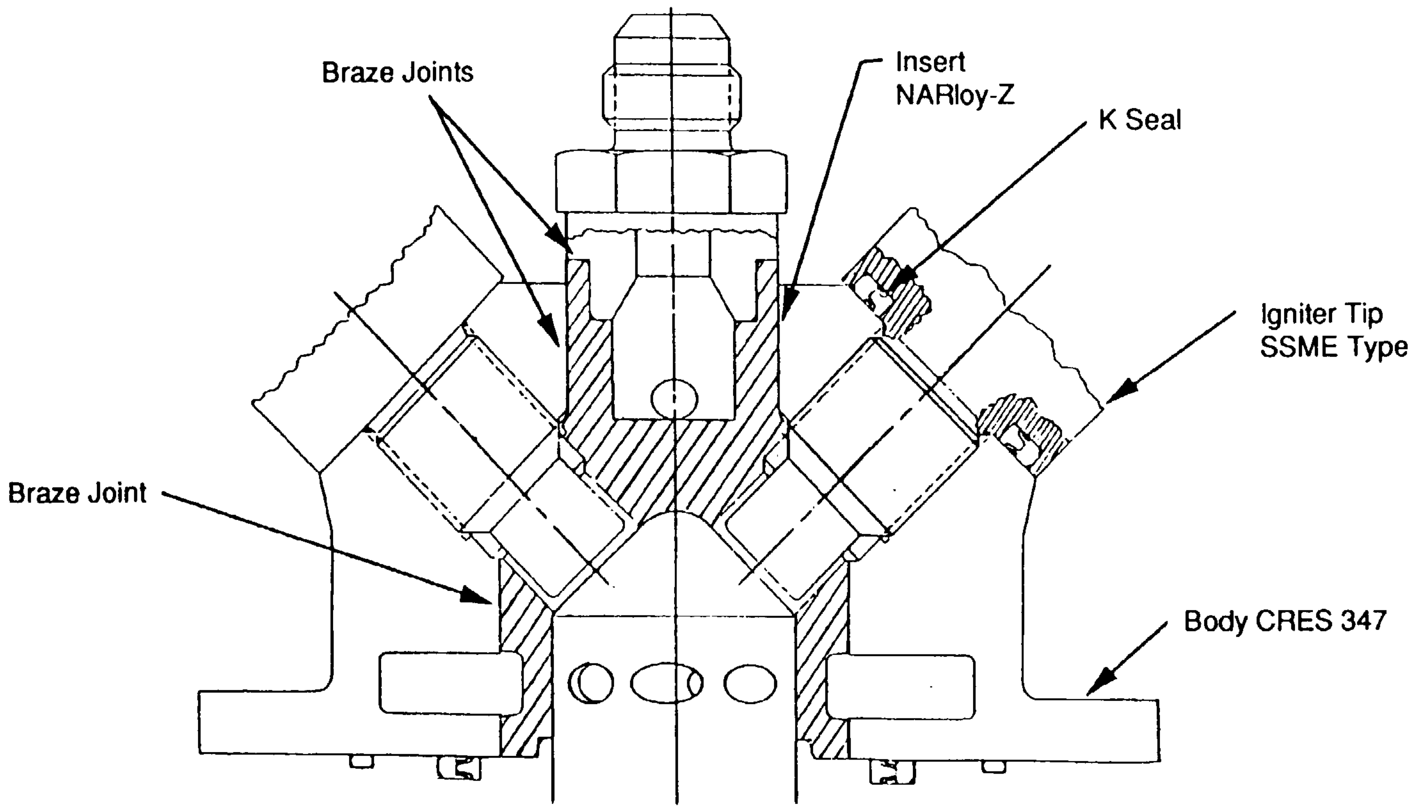
PROTOTYPE IGNITER ASSEMBLY
Igniter Mount Section



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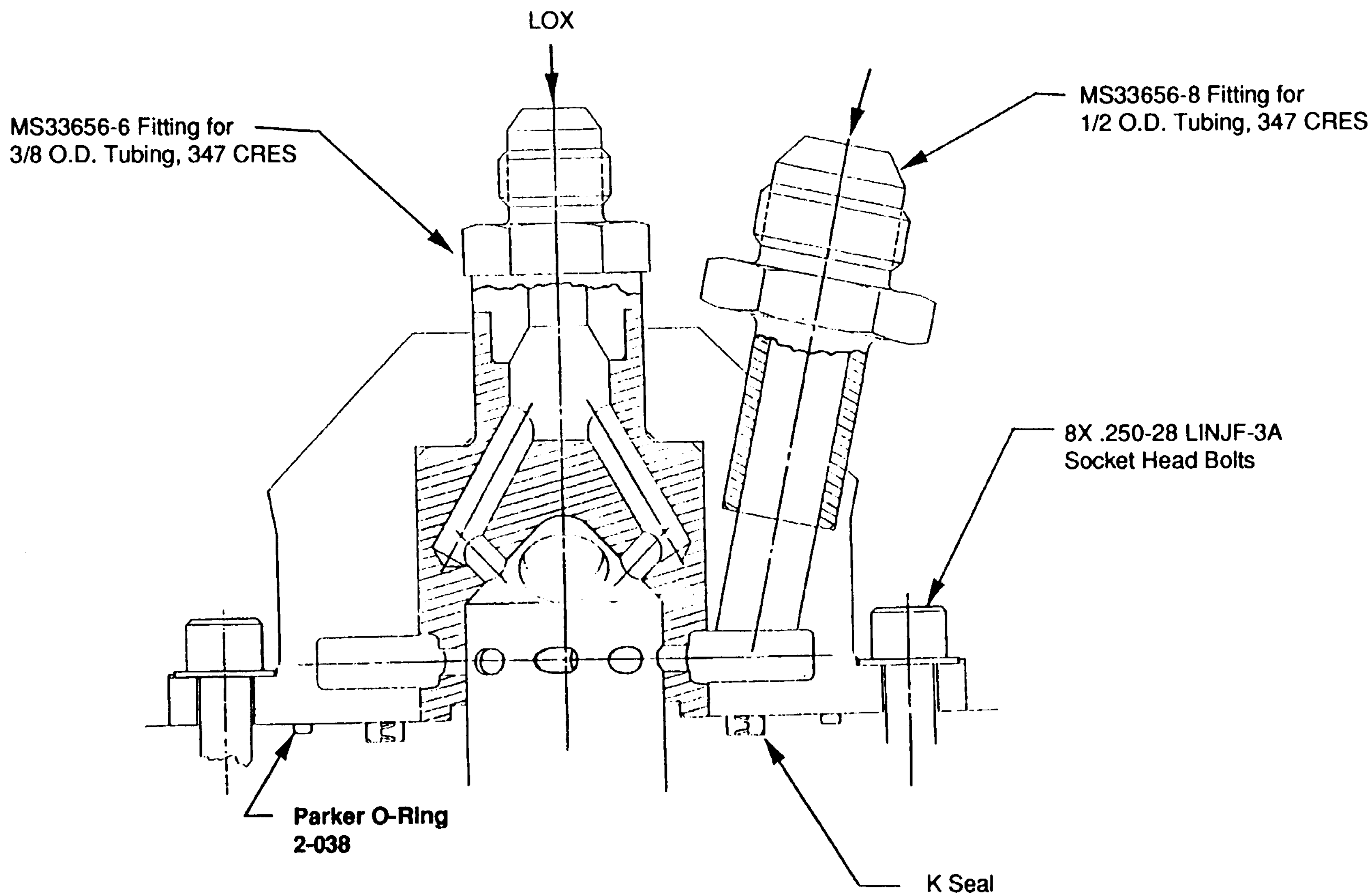
PROTOTYPE IGNITER ASSEMBLY
Propellant Feed Section



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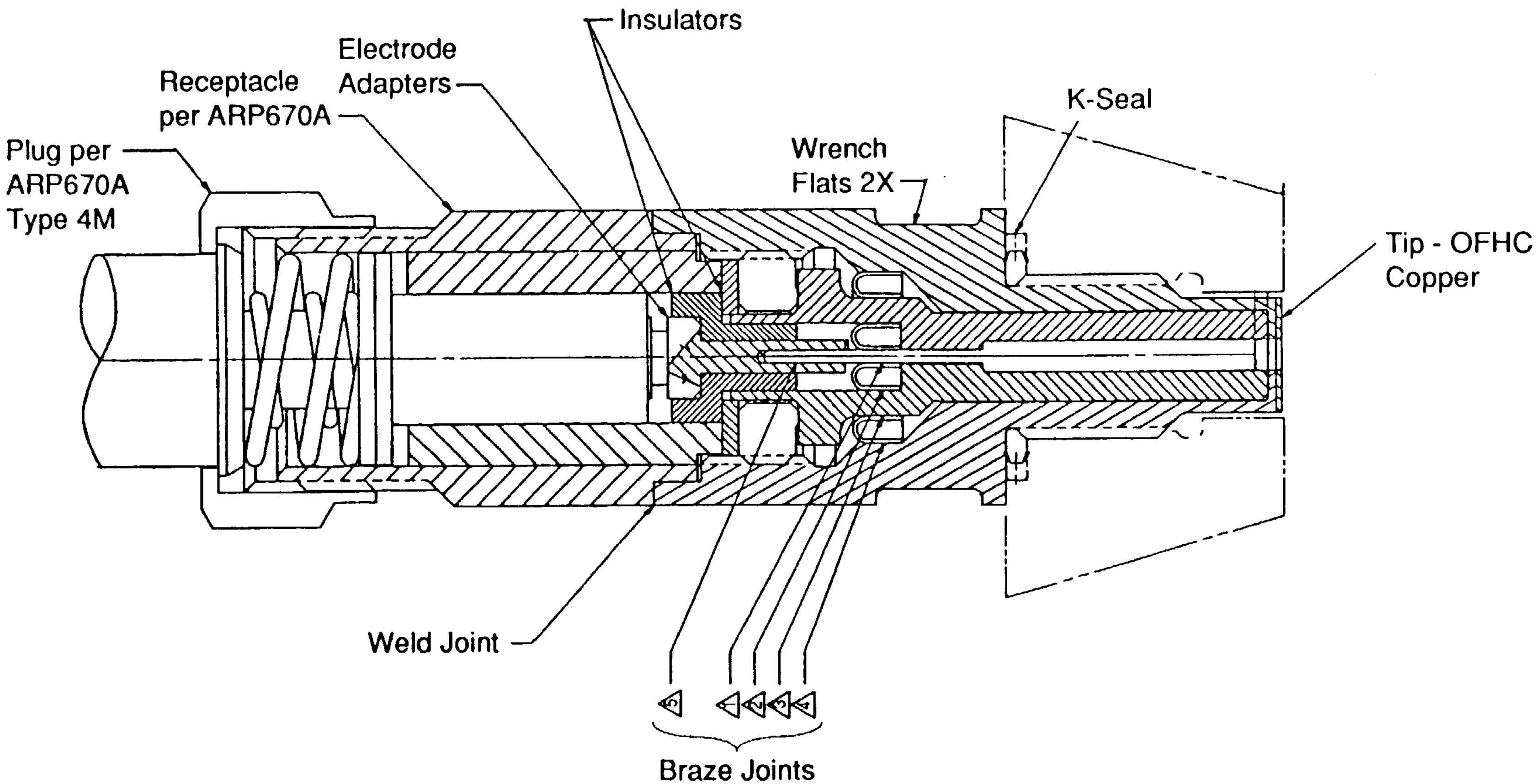
IGNITER SPARK PLUG ASSEMBLY



Rockwell Aerospace
Rocketdyne

95LS/043-A-016

PRELIMINARY IGNITION SYSTEM REQUIREMENTS

- **High reliability**
- **Flight engine compatible**
- **Low life-cycle cost**
    - Maximum factory build-up and check-out
    - Reusability consistent with engine life
    - Minimum maintenance and servicing
        - Readily serviceable when/if required
    - Minimum use of expendable components
- **Maximum safety**
    - Minimum use of hazardous materials
        - Hypergols, pyrotechnics, other toxics

PRELIMINARY ELECTRONICS REQUIREMENTS

- **Same electronics for all potential applications**
  - MCC ASI, GG ASI and GG direct spark systems
- **Dual, redundant electronics**
- **Reusable components**
  - Electronics life goal = life of engine
- **Separable, line replaceable, components**
  - Exciters, cables and igniter-plugs
- **Reduce costs associated with prior spark systems**
  - Integral igniter/exciter
  - Pressurized high voltage components

IGNITION SYSTEM SELECTION

- **Baseline system**
  - Electric spark-torch igniter
    - Main combustion chamber
    - Coaxial element gas generator injector
  - Direct electric spark system for GG
    - Splash plate gas generator injector
- **Options**
  - Identify candidate systems
  - Compare candidates to baselines via trade studies

IGNITION SYSTEM CANDIDATES

- **Concepts**
  - Catalytic ignition
  - Electric spark
    - Direct
    - Spark-torch
    - Combustion wave
  - Hypergol injection
  - Laser ignition (new technology)
  - Pyrotechnic
  - Resonance-torch

PRELIMINARY IGNITER SELECTION

- **Augmented spark-torch igniter (ASI) selected**
  - High reliability
    - Dual, redundant electronics
    - Demonstrated and flight proven (J-2 & SSME)
  - Flexibility
    - Adapted to widely varying start conditions
      - Pump and H.P. tank fed starts
        - J-2 engine with altitude start/re-start
        - J-2S engine with idle mode start
        - SSME (two designs, three operating regimes)
        - Used for high pressure facility systems
          - COCA 1A/1B, COCA 4B

PRELIMINARY IGNITER SELECTION

- **ASI selected**
  - Excellent engine compatibility
    - Starts from low pressure propellant tank pressures
    - Operates through engine power-up and mainstage
    - Simple torch design
      - No special cooling provisions
    - No pilot elements in main or GG injectors
    - Minimum need for propellant valves/sequencing
      - Igniter fuel valve not required
      - Flow shut-off not required during engine operation

PRELIMINARY IGNITER SELECTION

- **ASI selected (continued)**
  - Low life cycle cost
    - Complete factory build-up and check-out
    - Reusable
    - Low maintenance
    - No expendables (except onboard propellants)
  - Safe
    - No hazardous materials

ELECTRONICS CONCEPT OPTIONS

- **Capacitor discharge, high tension, high energy**
  - J-2 and J-2S ASIs
- **Capacitor discharge, low tension, shunted gap plug**
  - F-1 (early GG direct spark system)
- **Inductive discharge, high tension, low spark power**
  - SSME ASIs (3 applications)
    - May not be suitable for direct spark GG application
      - Low "peak" spark power
      - Effect of low peak power on plasma shape unknown

PRELIMINARY ELECTRONICS CONCEPT SELECTION

- **Capacitor discharge, high tension system (based on J-2 engine ignition system operation)**
  - Medium spark rate (approx. 40 sparks/sec)
  - Medium energy (approx. 90 mj/spark at plug)
  - High pressure quench resistance
  - Suitable for ASI and direct spark applications
  - Shielded exciter, cable and igniter back-shell
  - Surface gap igniter plug
  - Spark monitor circuit (at exciter)
  - Damage-free operation with sparks quenched
  - Damage-free operation with spark cable shorted

IGNITER RESULTS

- **Detail design review completed of housing details and assembly**
- **Completed detail drawings of housing assembly**
- **Design of spark plugs completed**
- **Electronics specifications written and released**
  - Spark igniter (RC2074)
  - High voltage cable (RC2075)
  - Ignition exciter (RC2076)

2.6 GAS GENERATORS

The gas generator effort was split into two areas: 1) a prototype gas generator for use on the engine, and 2) a workhorse gas generator for use in testing the engine turbopumps.

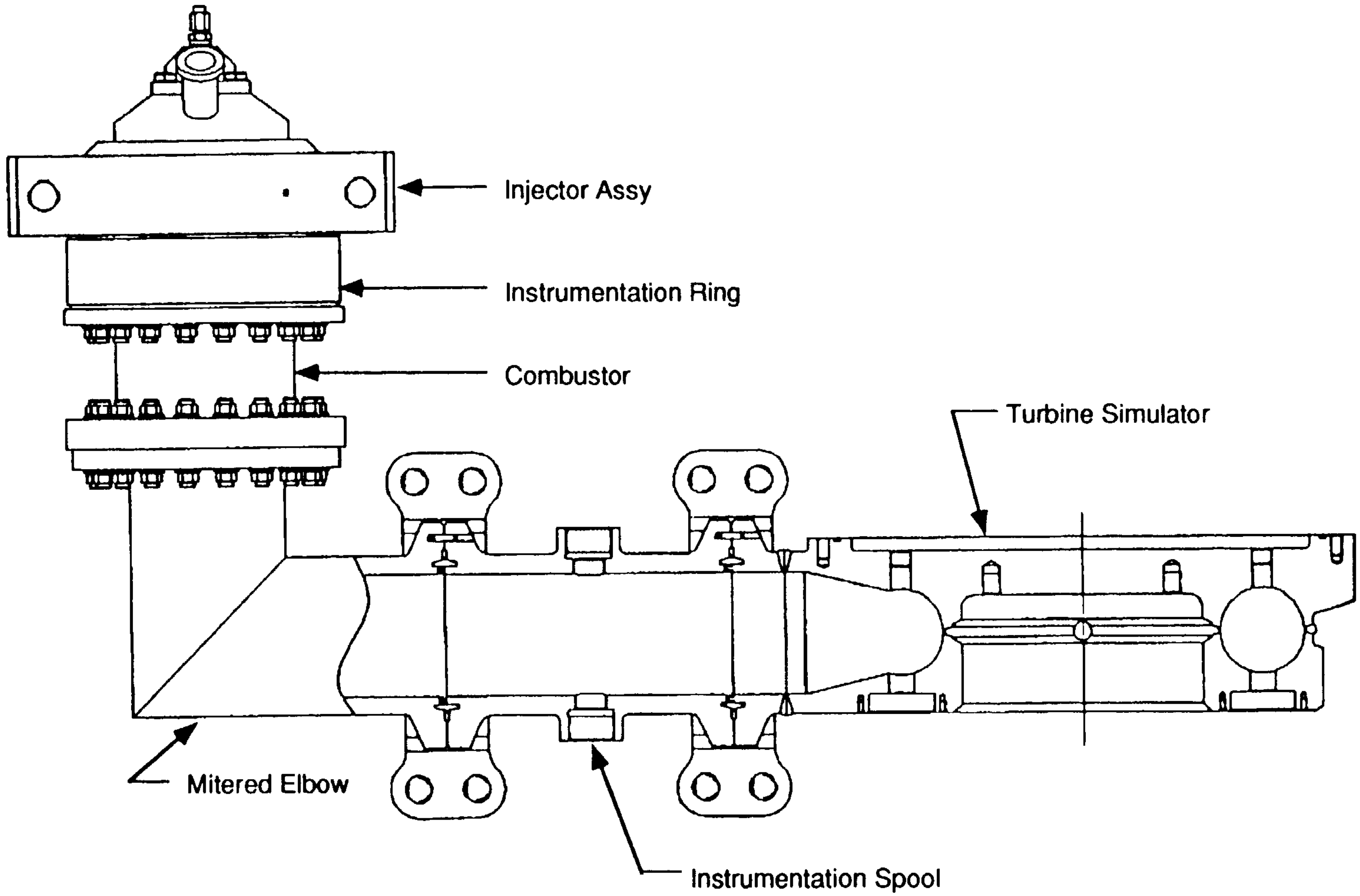
The prototype gas generator was designed accommodate three different injector assemblies. The inclined fan injector was most adaptable to low cost manufacturing methods. The coaxial injector had a proven record of performance and reliability on the SSME and J-2 engines. The "box pattern" injector had the greatest performance potential. The different designs were to be evaluated for performance and wall compatibility through hot-fire testing. The fabrication costs would then be factored in to select the appropriate injector.

The workhorse gas generator was designed to test turbopumps from Aerojet, Pratt & Whitney, and Rocketdyne. The differing requirements from the three companies were best attained by utilizing a coaxial injector design. A turbulator was added to ensure good mixing of the combustion gas before entrance into the turbopump.

The gas generator effort is summarized in the charts that follow.

2.6.1 PROTOTYPE GAS GENERATOR

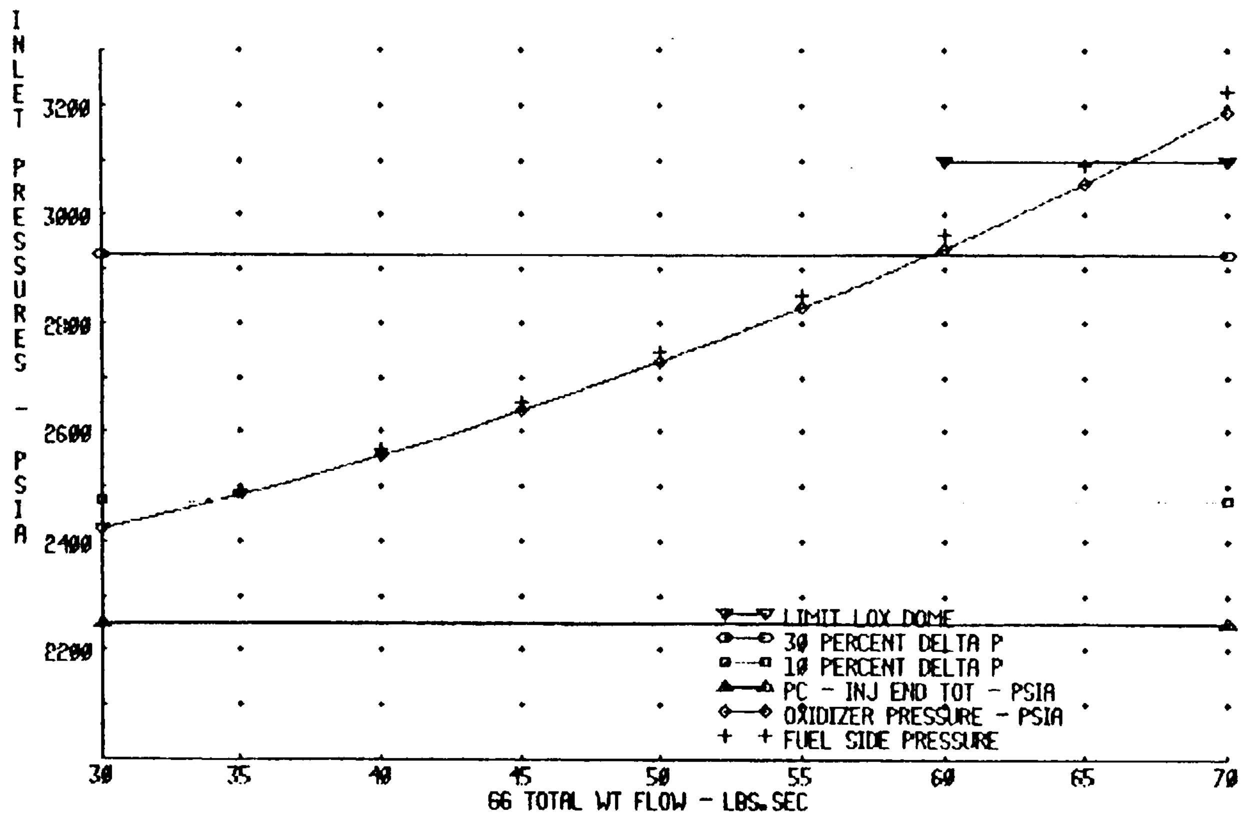
PROTOTYPE GAS GENERATOR ASSEMBLY



PROTOTYPE GAS GENERATOR OPERATIONAL ENVELOPE

- **Design point**
  - Chamber pressure 2250 psia
  - Chamber temperature 1600°R
  - Wt flow 49.8 lbs/sec (injector flow)
- **Envelope limitations**
  - Both propellants liquid ("square law" ΔP effects)
    - Low flow limited by low ΔP - stability concerns
    - High flow - high ΔP - Structural limits
- Facility limits
  - Operating conditions based on turbine
    - Reworked for higher flow - fixed Pc
    - Fixed flow area (inlet nozzle) variable Pc

EFFECTS OF TOTAL FLOW ON PROTOTYPE GG PRESSURE



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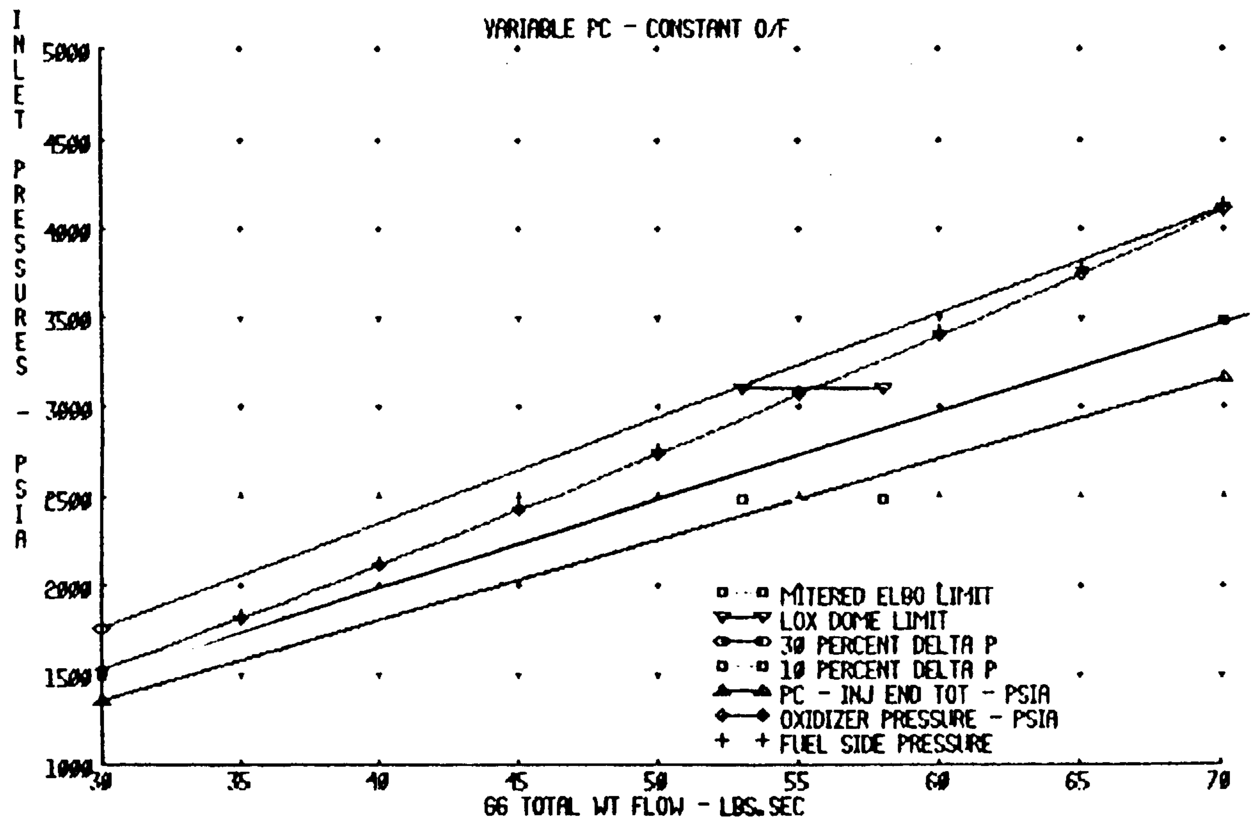
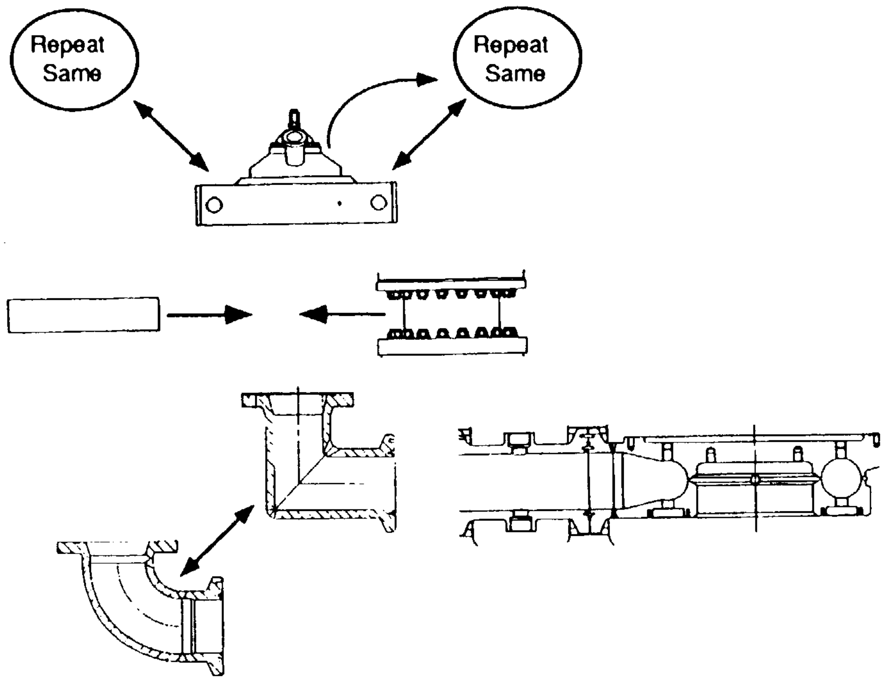
EFFECTS OF TOTAL FLOW ON PROTOTYPE GG PRESSURES



PROTOTYPE GAS GENERATOR COMPATIBILITY OPTIONS

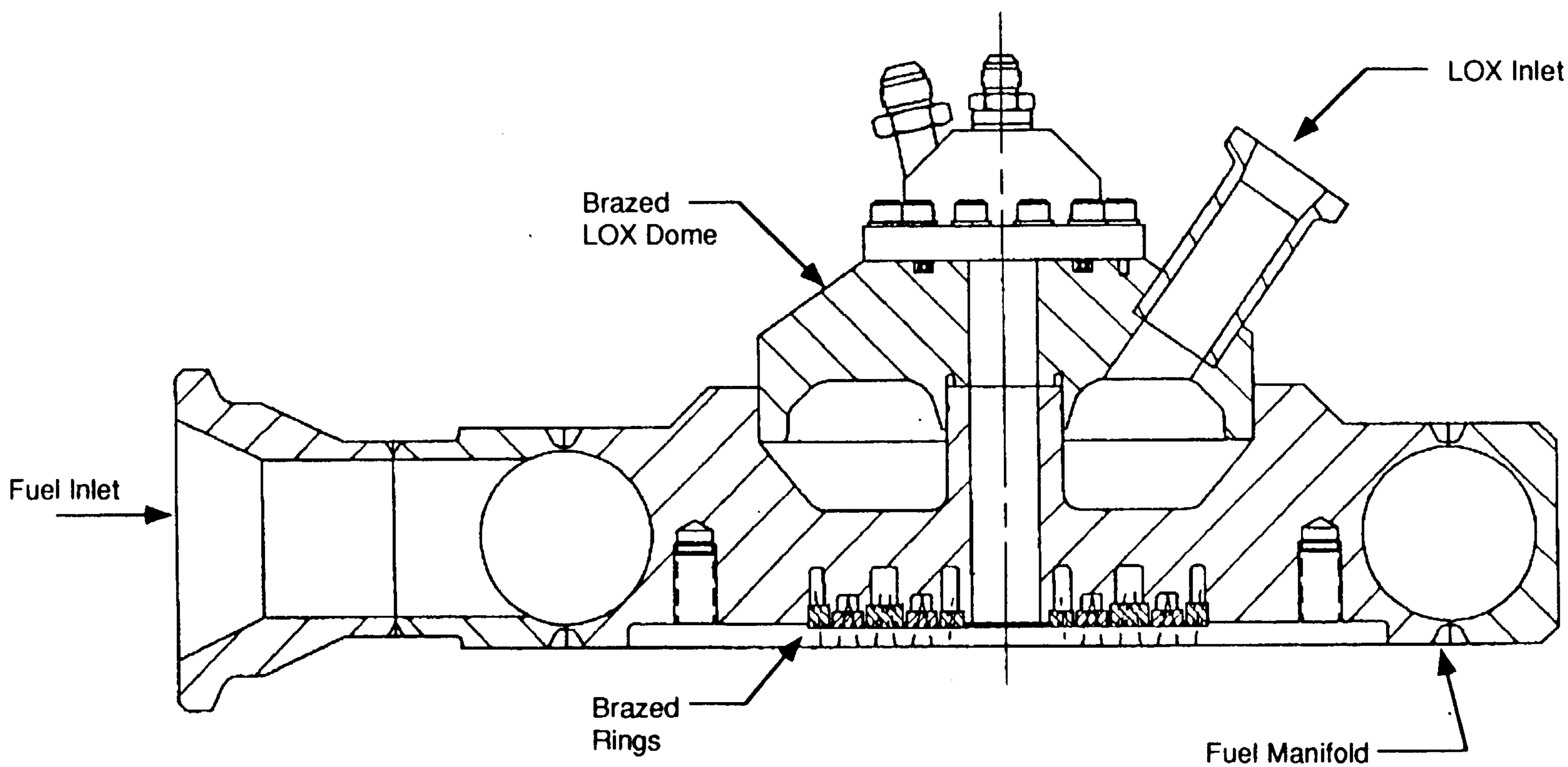


- All interfaces common between 3 gas generator injector assemblies
- All injectors have same ignition system and LOX dome
- All injector/bolt combustor patterns the same
- Both elbow configurations interchangeable
- Allows for varying combustion chamber length

PROTOTYPE GAS GENERATOR INJECTOR OPTIONS

- **Incline fan injector**
  - Flat face easily adapted to casting
- **Coaxial injector**
  - Similar to SSME preburners and J-2 main injector
- **Box pattern injector**
  - Predicted improvements in mixing efficiency, combustion efficiency, and stability over classic impinging injectors

PROTOTYPE INCLINED FAN INJECTOR PROFILE



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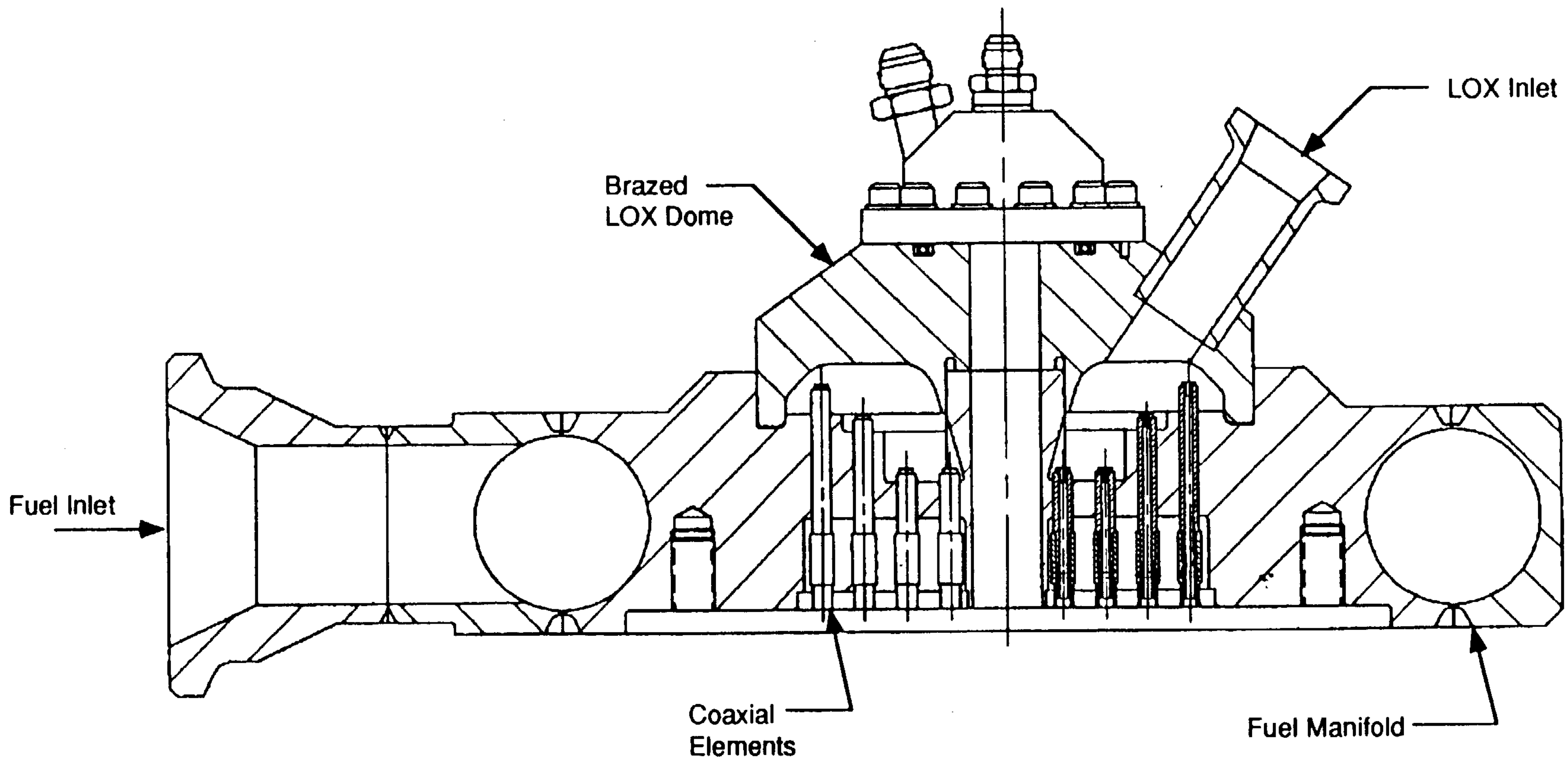
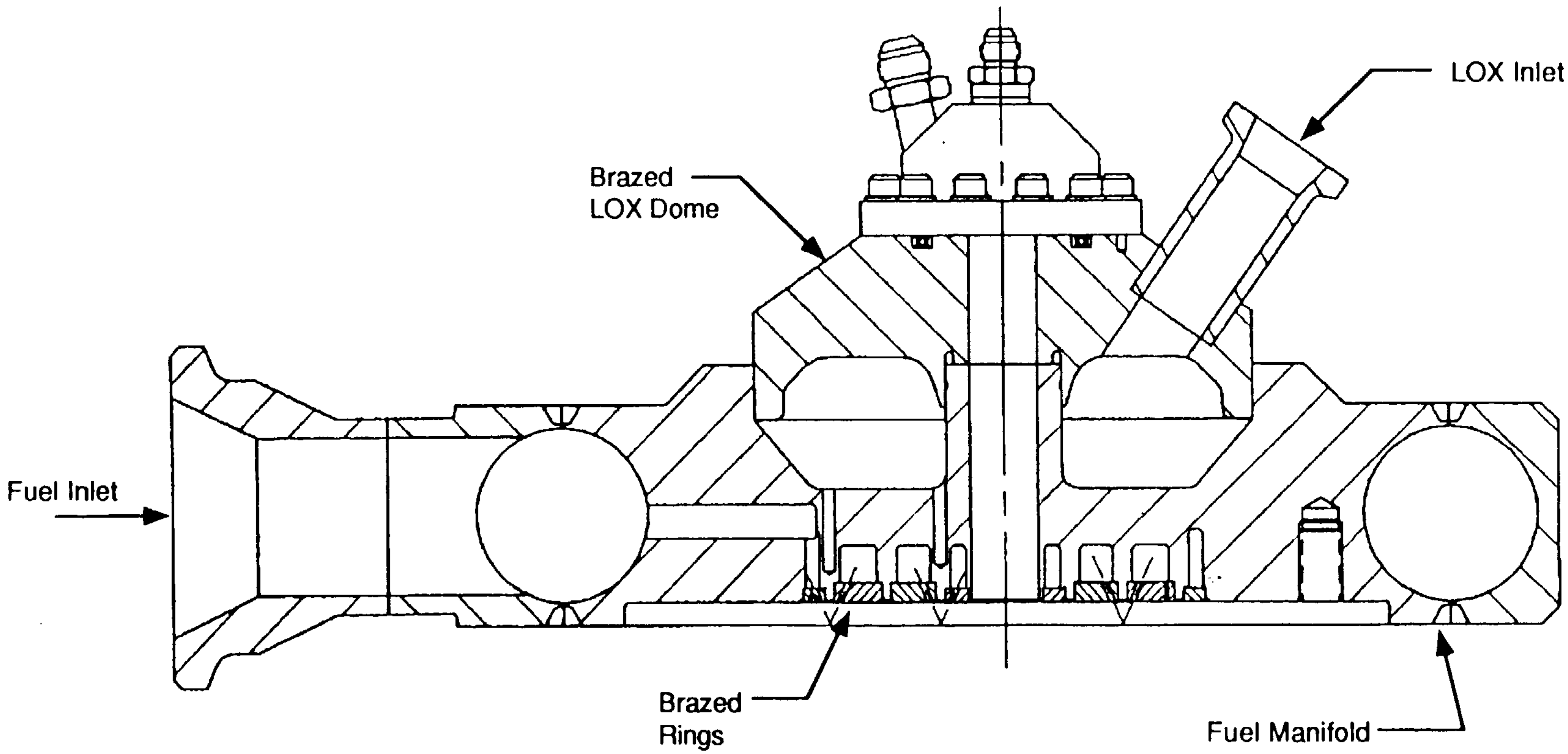
PROTOTYPE COAXIAL INJECTOR PROFILE



PROTOTYPE BOX PATTERN INJECTOR PROFILE



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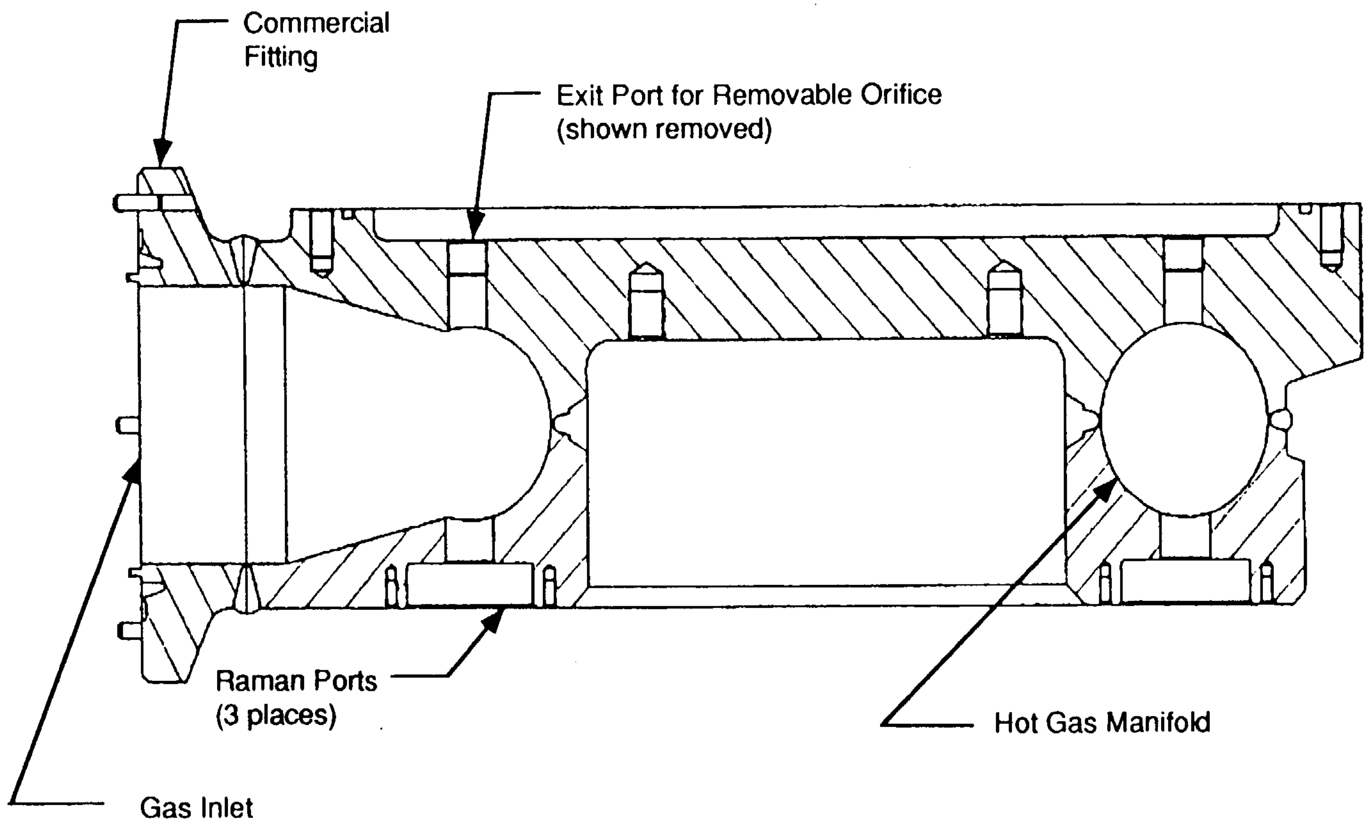
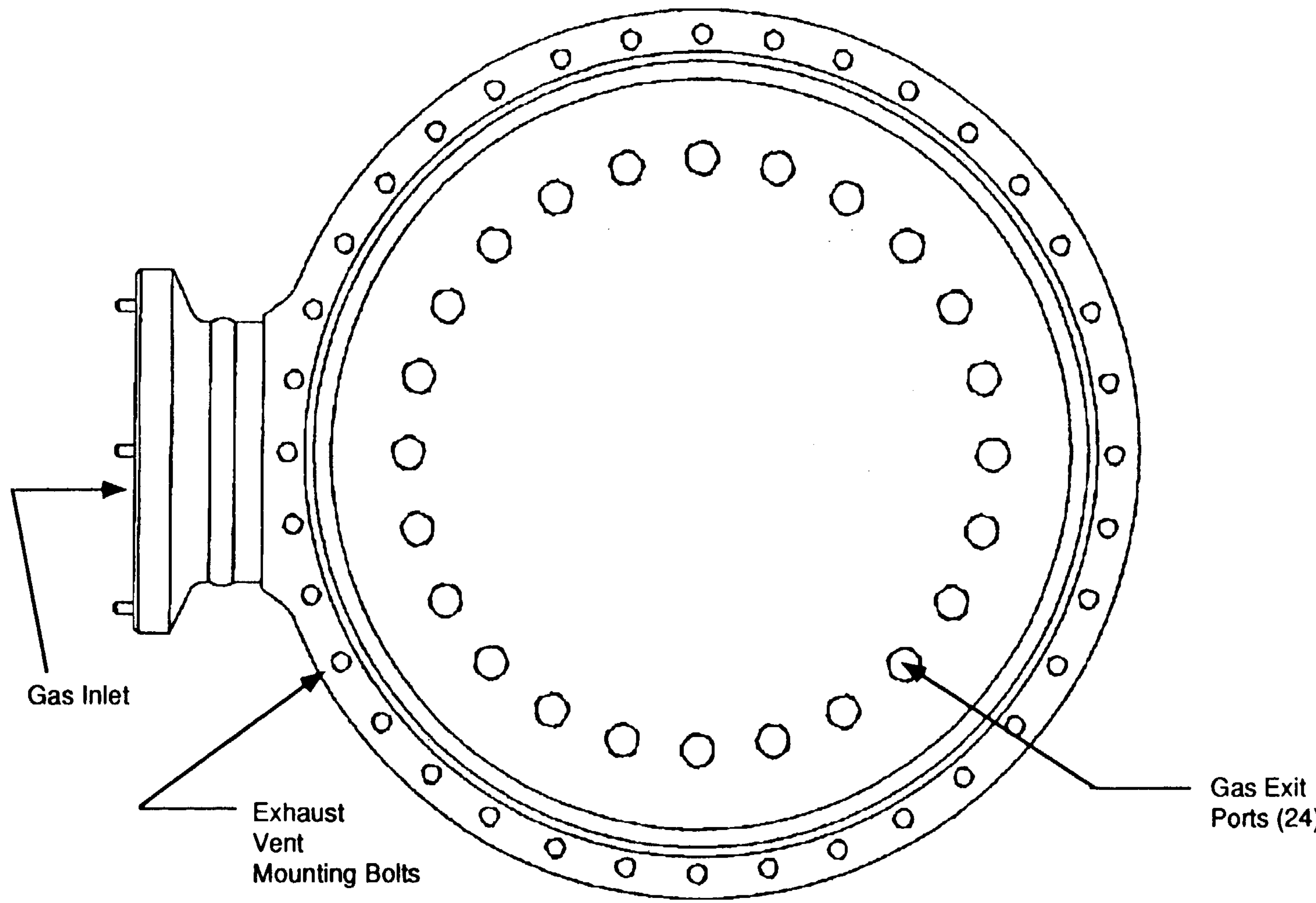
PROTOTYPE GAS GENERATOR TURBINE SIMULATOR

- Represents the necessary back pressure for the gas generator
- Constant diameter torus represents manifolding planned for engine
- 24 - .488" diameter orifices simulate first stage nozzle
- Orifices threaded in to accommodate changes in diameter
- Instrumentation profile to identify first stage nozzle environment

SECTION VIEW - TURBINE SIMULATOR



TURBINE SIMULATOR DISCHARGE



PROTOTYPE INJECTORS

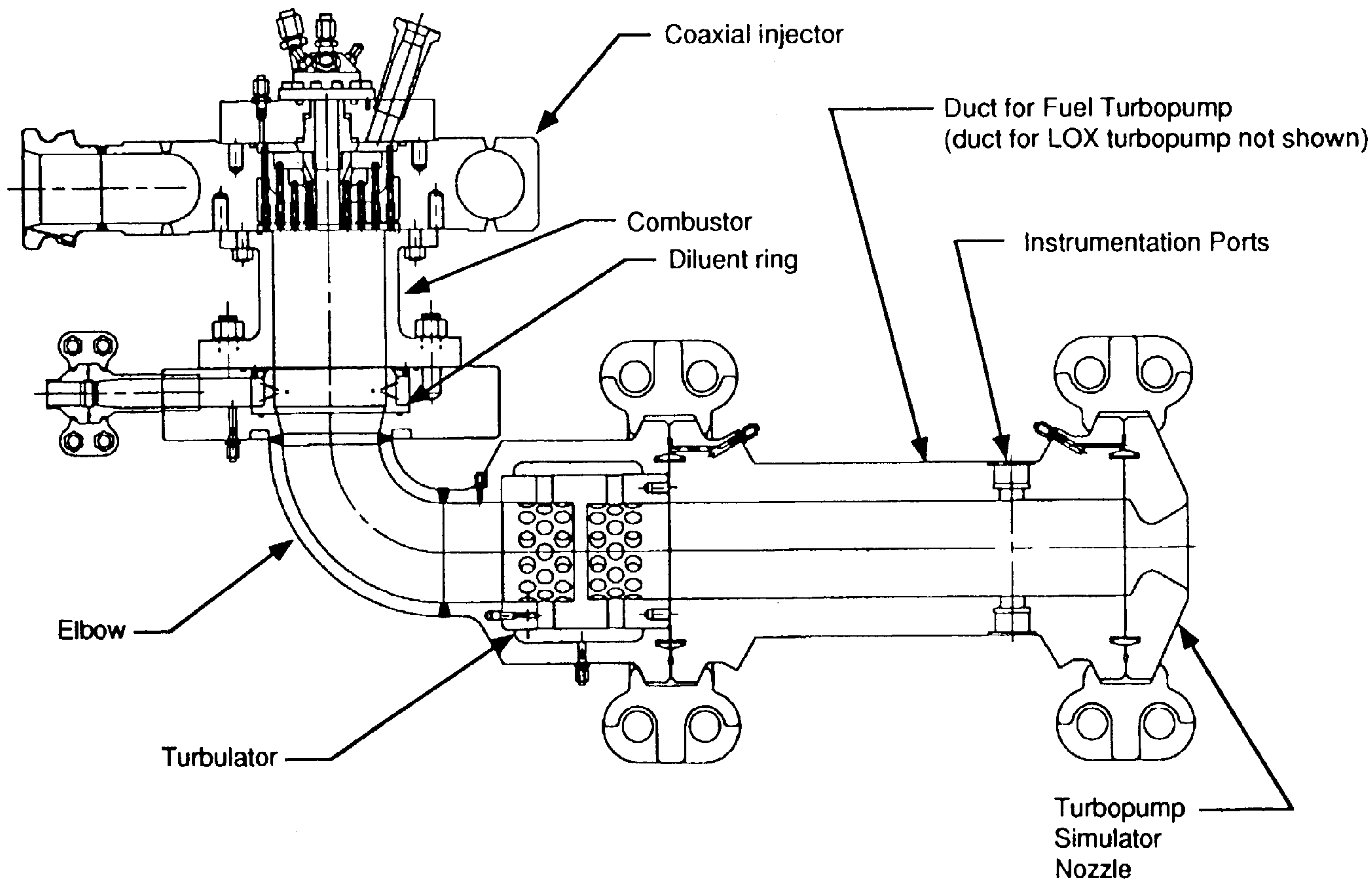
	"Box" Like Doublet	Inclined Fan "Coarse" Like Doublet	COAX
Performance			
Temp Profile	Good: Maximized mixing with fuel encompassing oxidizer	High Risk: Classic edge mixing like doublet coarse pattern	Good: Classic coax properties fuel around oxidizer-face bleed
C-Star Eff	Good: Maximized mixing impinging atomization	Good: Doublet mixing but possibly some stream zones between rows	Good: However, extended LOX vaporization - requires longer length
Stability	High Risk: Smaller elements - impinging more sensitive	High Risk: Coarser element than "box", but still hazardous	Good: Classic coax good stability - but liquid fuel concern
Durability	Risk: Impinging pattern-re-circulation conductive face required	High Risk: Coarser pattern - more recirculation larger uncooled areas	Good: Transpiration face cooling - rugged elements
Fabrication	Most Complex-Critical orifice generation and manifold configuration	Lowest Cost-Best suited to casting - coarse injection pattern	All"State of Art" but more operations than "coarse" doublet - highest cost
Reliability Critical Items	Outer fuel ring plugged orifices, ring/land joint braze failure	Outer fuel ring plugged orifices, ring/land joint braze failure	Lost post cracked/broken, braze joint failure

PROTOTYPE GAS GENERATOR RESULTS

- **Three injector designs completed**
  - Inclined fan
  - Coaxial
  - Box pattern
- **Detailed design and analysis of all hardware completed**
  - Instrumentation ring
  - Combustor
  - Elbow
  - Instrumentation spool
  - Turbine simulator
- **Detailed drawings of all hardware released**

2.6.2 WORKHORSE GAS GENERATOR

WORKHORSE GAS GENERATOR



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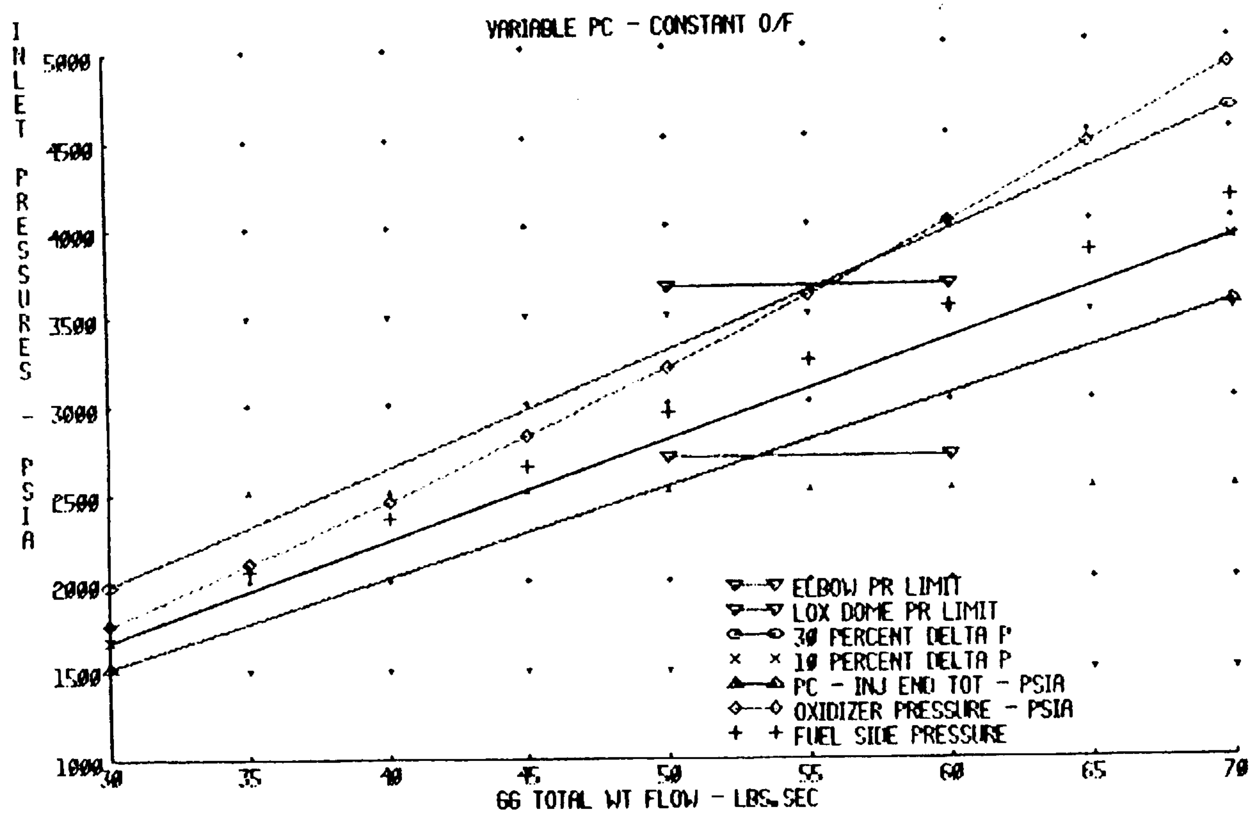
DESIGN REQUIREMENTS

Parameter		Aerojet	Rocketdyne	P&W
Nominal Turbine Inlet Pressure	PSIA	1900	2239	486
Maximum Turbine Inlet Pressure	PSIA	---	2565	550
Nominal Turbine Inlet Temperature	°R	1600	1600	1365
Maximum Turbine Inlet Temperature	°R	1660	1660	1450
Nominal Hot Gas Flowrate	lbs/sec	50.3	46.0	46.0
Maximum Hot Gas Flowrate	lbs/sec	---	53.0	57.0
ASI Total Flowrate	lbs/sec	.5	.5	.5
Exhaust H_2 Coolant Flowrate	lbs/sec	---	---	5.2

WORKHORSE GAS GENERATOR
Gas Generator Limitations

- **Baseline design points**
  - Total Flow 49.8 lb/sec
  - Pc 2250 PSIA
  - 1600°R (at .77 O/F)
  - LOX ΔP 30% of Pc
  - Fuel ΔP 20% of Pc
- **Limiting conditions**
  - Low flow
    - Low ΔP atomization and feed system stability
  - Higher flow
    - Structural pressure limits
    - Facility pressure limits
  - Operating conditions based on turbine
    - Reworked for higher flow - fixed Pc
    - Fixed flow area (inlet nozzle) variable Pc

EFFECTS OF TOTAL FLOW ON WORKHORSE GG PRESSURES



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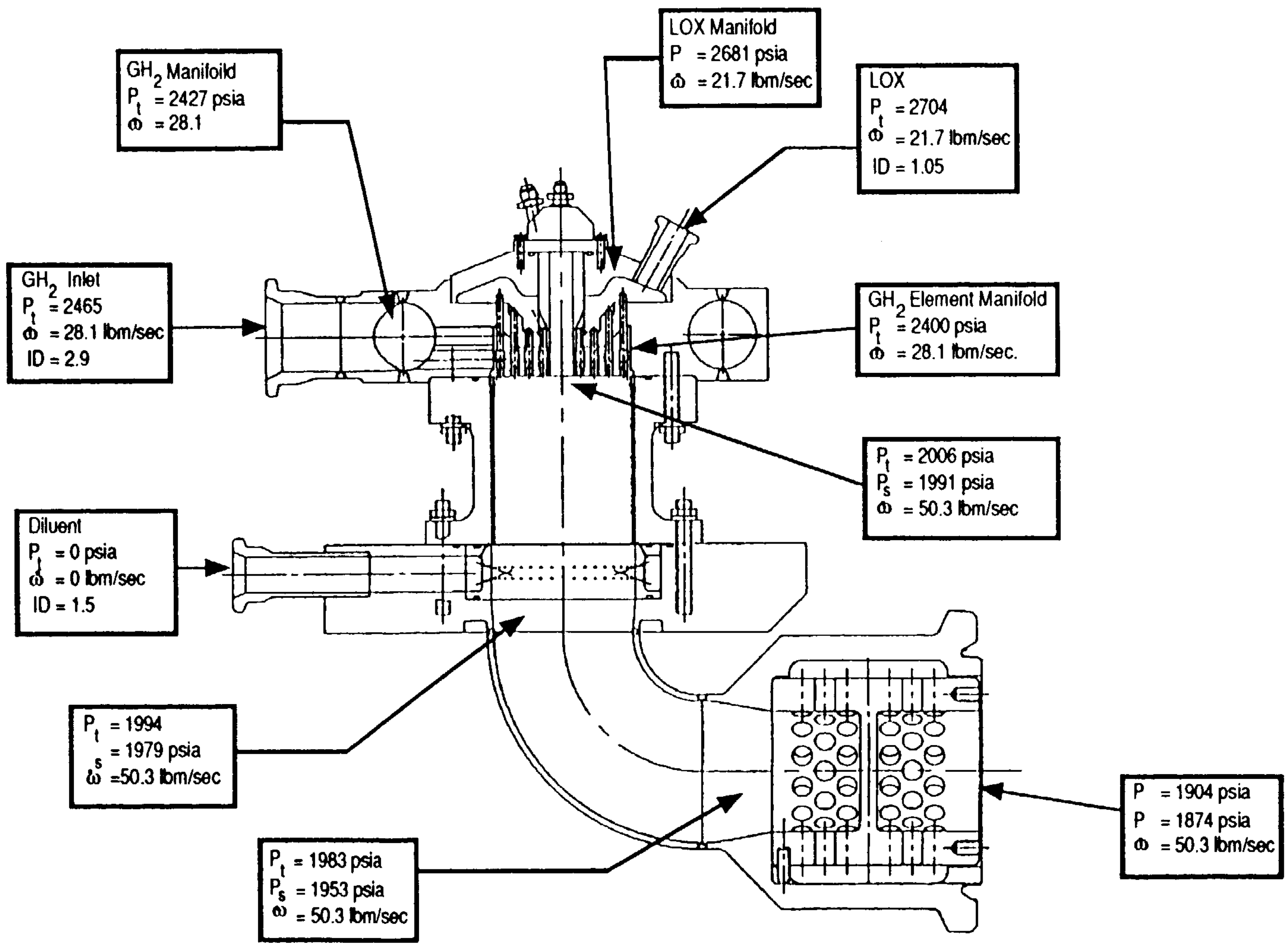
PRESSURE DROP THRU WORKHORSE GGA

For Aerojet Turbopump Operation



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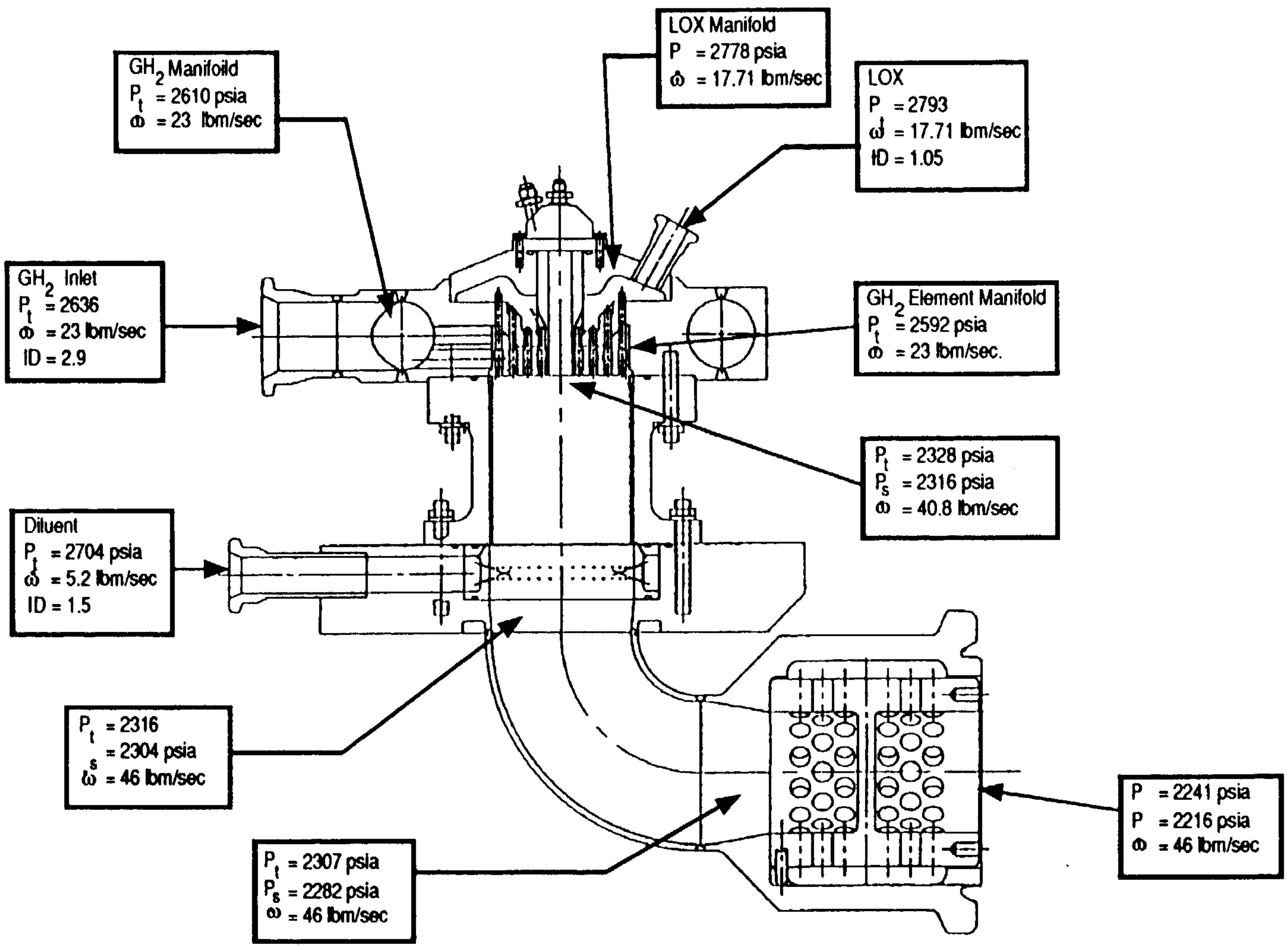
PRESSURE DROP THRU WORKHORSE GGA

For Pratt and Whitney Turbopump Operation



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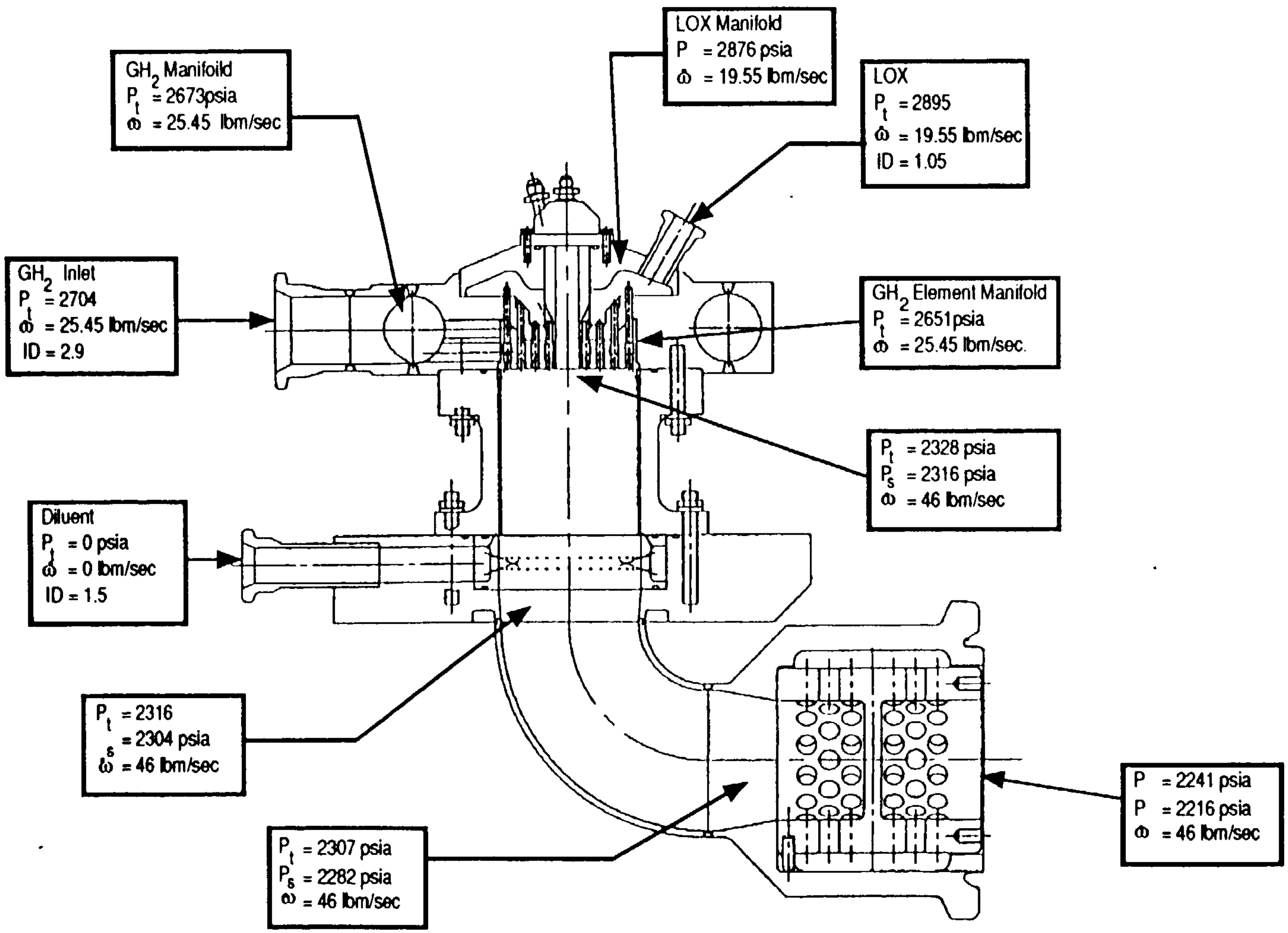
PRESSURE DROP THRU WORKHORSE GGA

For Rocketdyne Turbopump Operation



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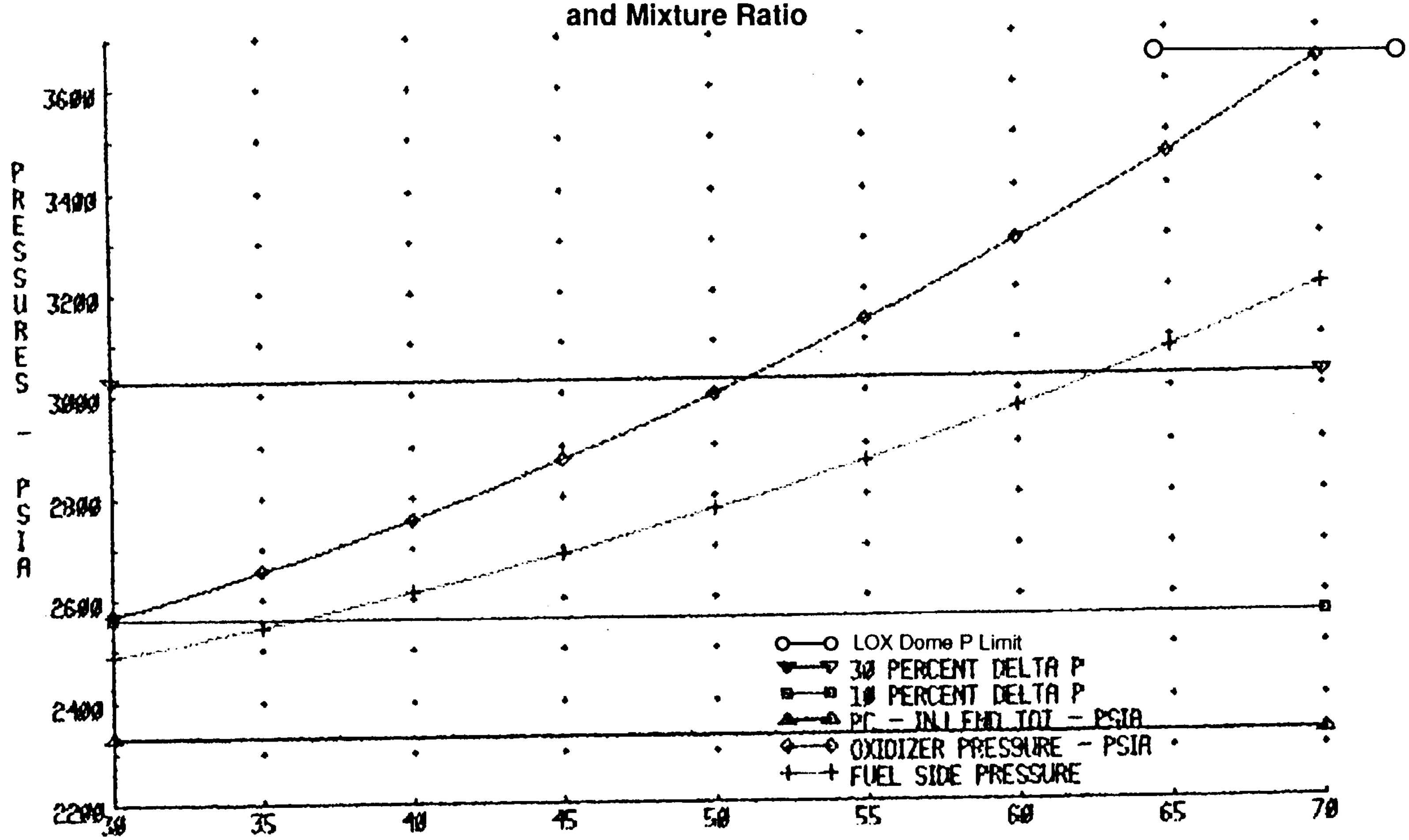
WORKHORSE GG OPERATIONAL ENVELOPE

Constant Chamber Pressure and Mixture Ratio



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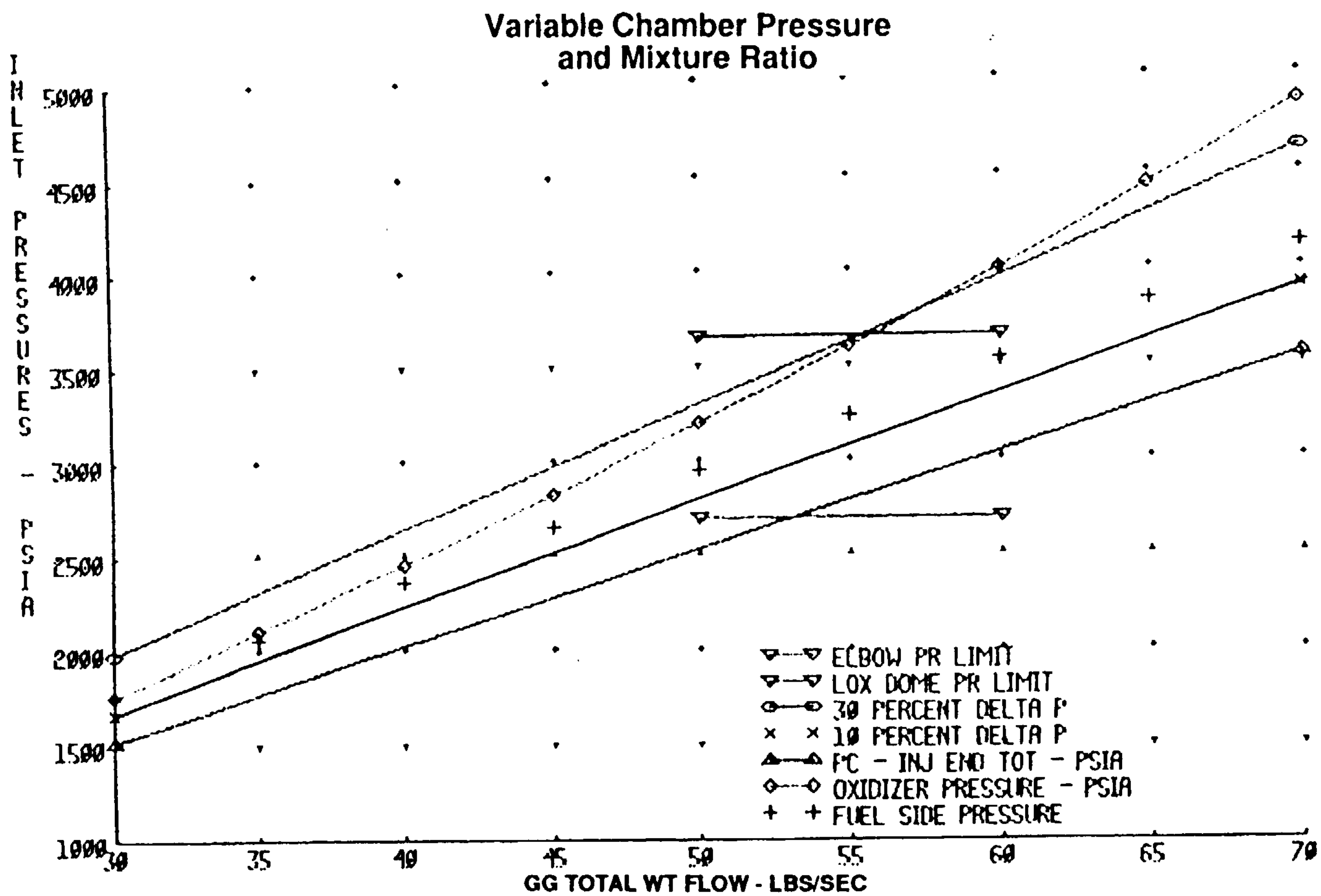
WORKHORSE GG OPERATIONAL ENVELOPE



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WORKHORSE GAS GENERATOR RESULTS

- **Facility interface control document (ICD) completed**
- **Detail design and analysis of all hardware completed**
  - Injector assembly
  - Combustor
  - Elbow
    - Diluent ring
    - Turbulator
  - LOX and fuel turbopump ducts
  - Turbopump simulator nozzles
- **Detail drawings of all hardware nearly completed**

3.0 COMPLIMENTARY STEP ACTIVITIES

After cancellation of work on the Advanced Development Program, some work was continued at Rocketdyne on the combustion chamber under the Space Transportation Engine Program (STEP). Since there was not enough funds available to build and test different combustion chamber designs, the concepts were thoroughly analyzed to select the concept to be tested when funds were made available (none ever were).

Besides the VPS and LIDB designs developed at Rocketdyne, the platelet liner design proposed by Aerojet were reviewed. This was a unique but difficult experience due to the proprietary nature of the processes used in the designs, but the resulting analysis was thorough and as unbiased as possible. Actual fabrication and test data would be very desirable in the future since all the concepts had high potential. Later in the program an ablative type combustion chamber design was developed for a low cost expendable version of the STEP engine. The charts that follow describe this effort in detail.

3.1 COMBUSTION CHAMBER CONCEPT RE-EVALUATION

COMPLIMENTARY COMBUSTION CHAMBER ACTIVITIES ON STEP FUNDING

- **Concept comparison**
  - LIDB
  - VPS
  - Platelet
- **Derivative engine ablative combustion chamber**

THREE CONCEPTS COMPARED

- **LIDB combustion chamber**
  - Wrought liner, cast aft manifold, EDNiCo structure
- **VPS combustion chamber**
  - Integral cast jacket, HIPed cold wall, VPS NARloy-Z hot wall
- **Platelet combustion chamber**
  - Integral cast jacket, platelet panels HIP-bonded to casting

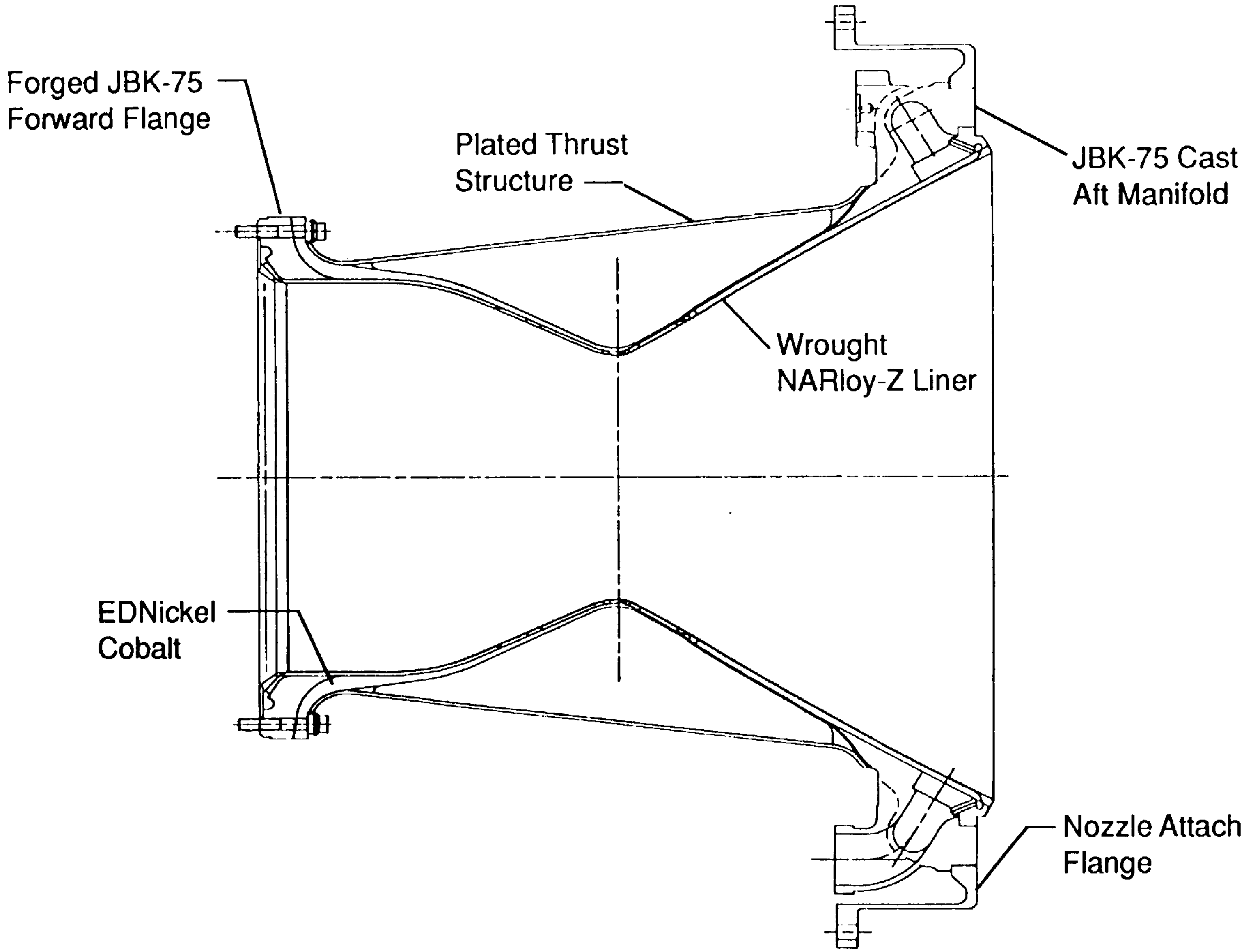
GROUNDRULES FOR COMPARISON

- **Be as objective as possible**
  - Rate concepts on all aspects of customer goals
  - Understand each concept at about an equal level
  - Let the customer rate which features are more or less important
- **Obtain consensus on comparison values**
- **NASA CDT members committed to evaluation results**
- **This is a concept review, everything will not be analyzed to the Nth degree**
  - The evaluation is not meant to be numerically precise, just directionally accurate
  - Concepts are compared to a LIDB concept baseline

COMBUSTION CHAMBER SELECTION
Process Maturity Demonstrations

- **LIDB/EDNi-Co**
  - Test LSI combustion chamber beginning Sept. '92
- **Platelet**
  - Test 40K chamber beginning June '92
  - Complete large scale MTD in Nov. '92
- **VPS**
  - Focus all VPS work in MSFC VPS facility
  - Continue parameter and material property development
  - Produce a large scale MTD by Jan. '93
    - NASA provide SSME-size jacket castings
  - Produce a 40K VPS throat for hot-fire by Jan .93

LIDB/EDNi Co COMBUSTION CHAMBER



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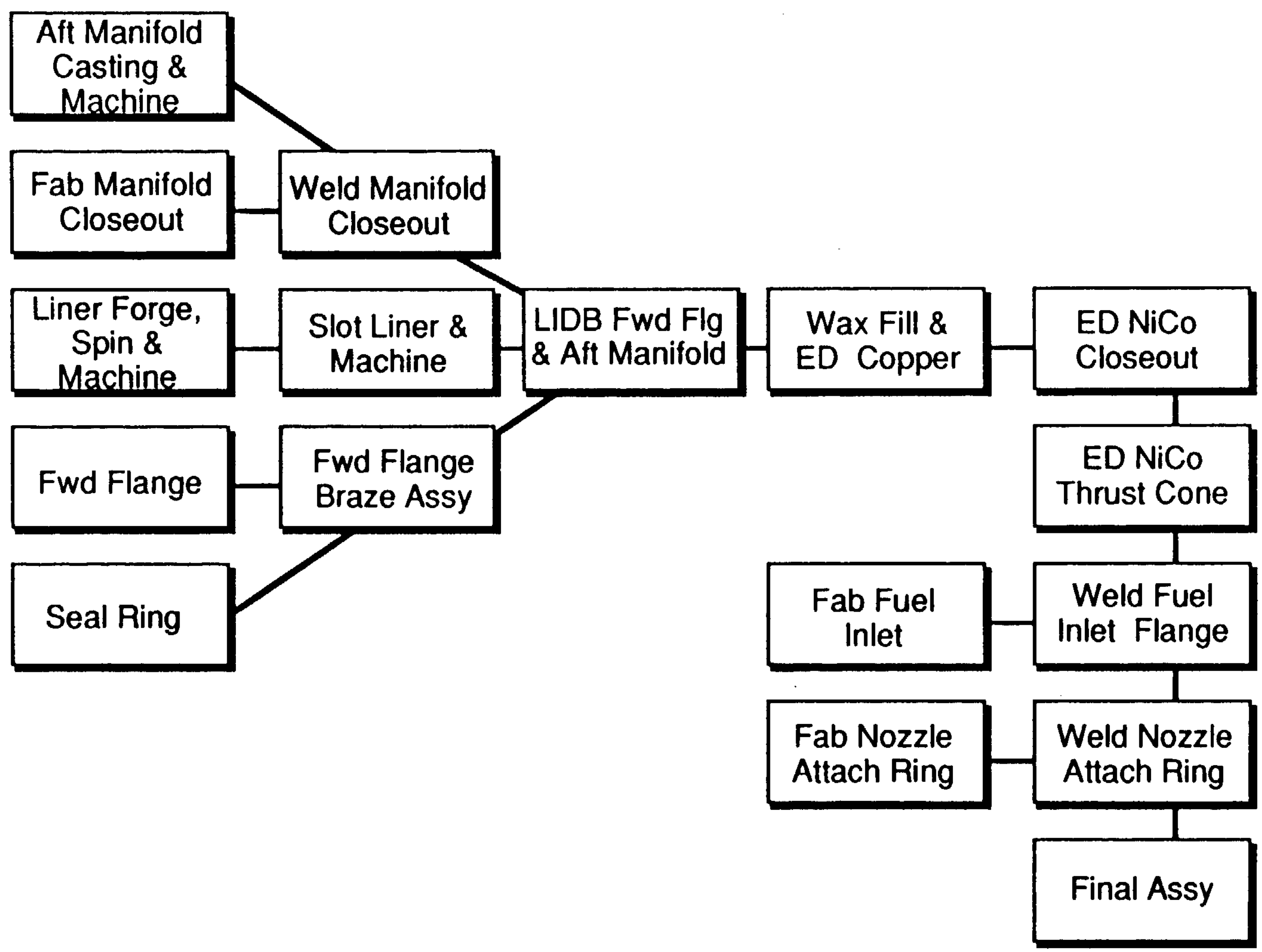
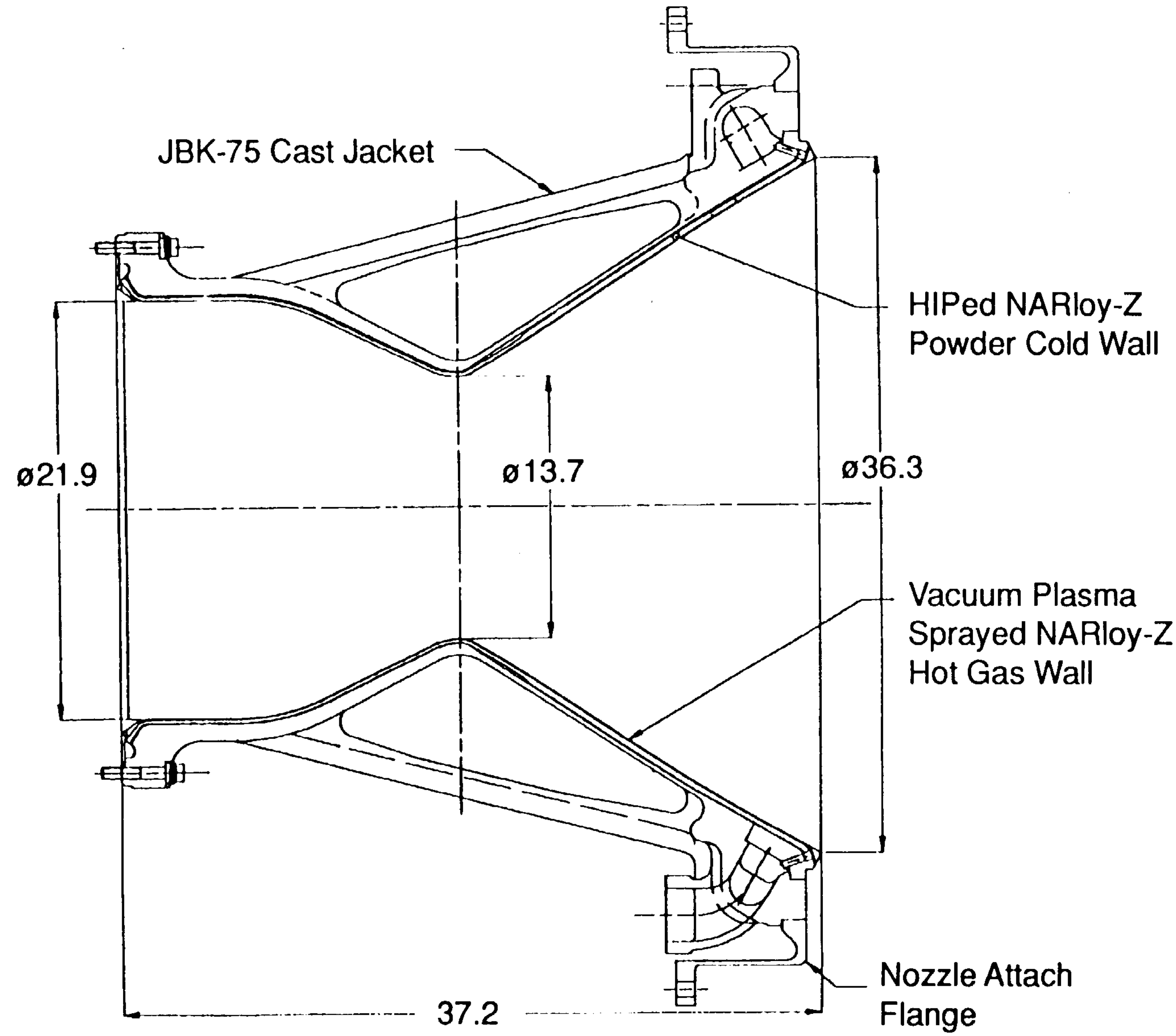
LIDB/EDNi Co COMBUSTION CHAMBER
Fab Flow



VPS COMBUSTION CHAMBER



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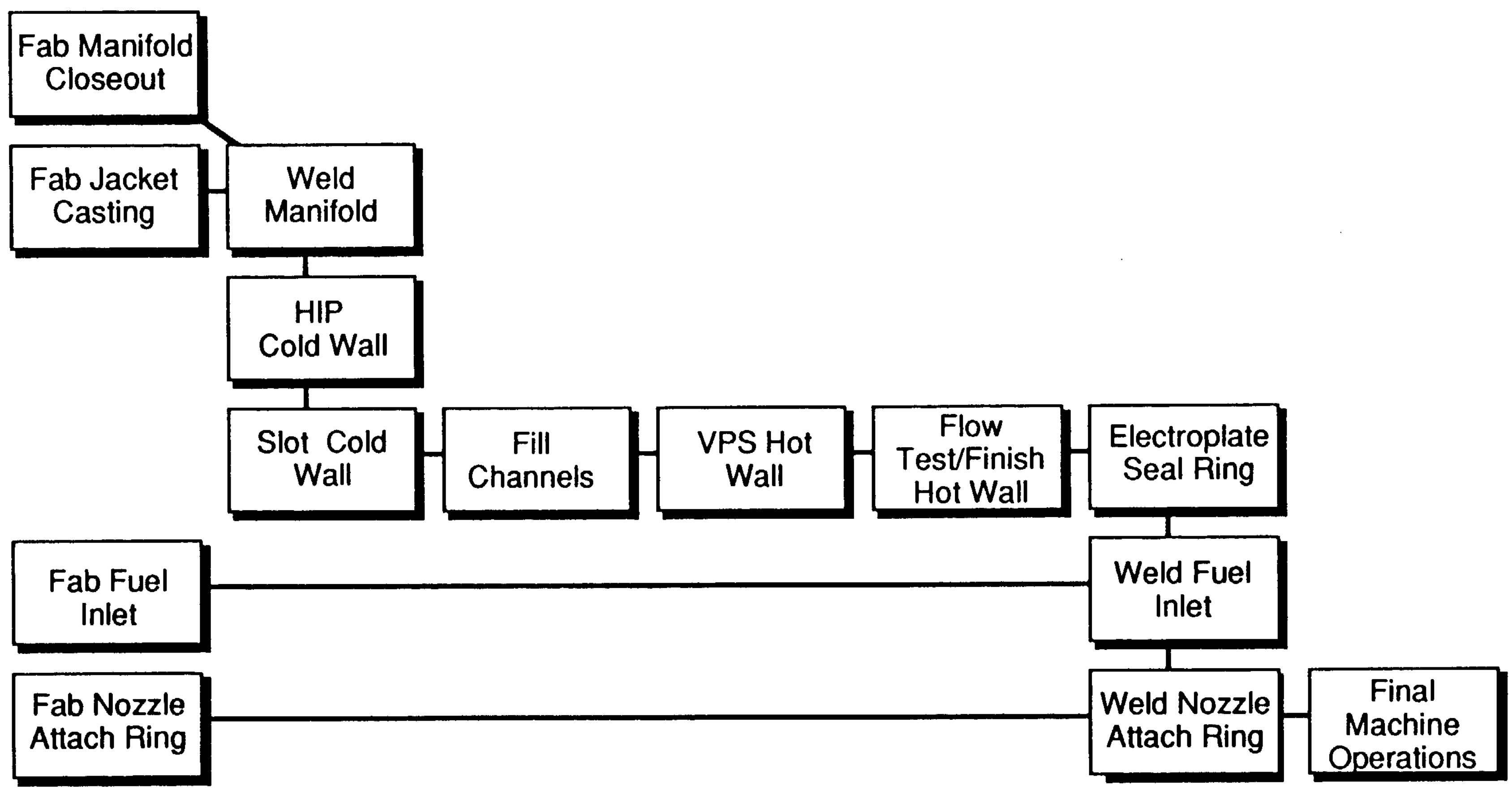
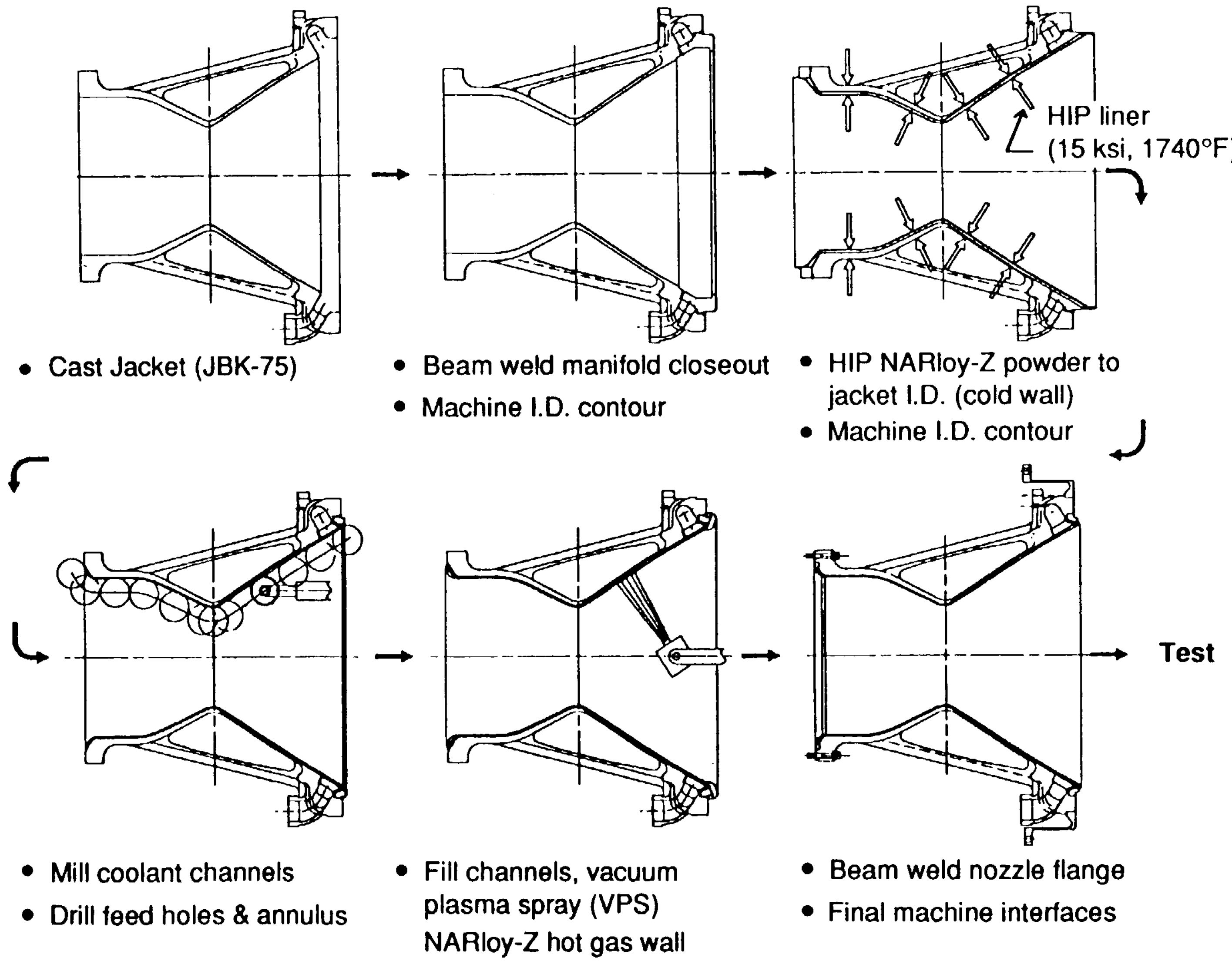
CAST JACKET/VPS LINER COMBUSTION CHAMBER

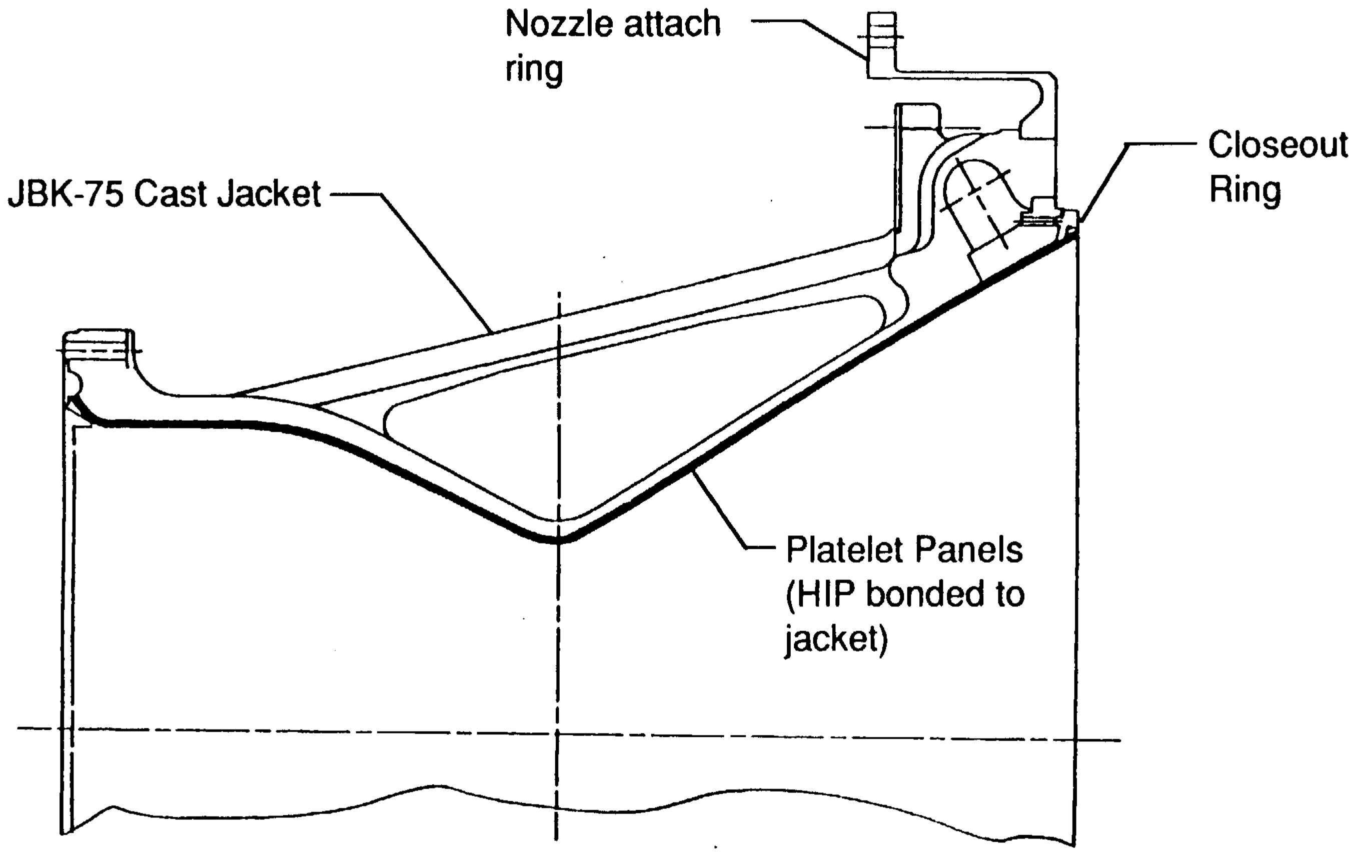
Fab Flow



CAST JACKET/VPS LINER FAB FLOW



PLATELET COMBUSTION CHAMBER



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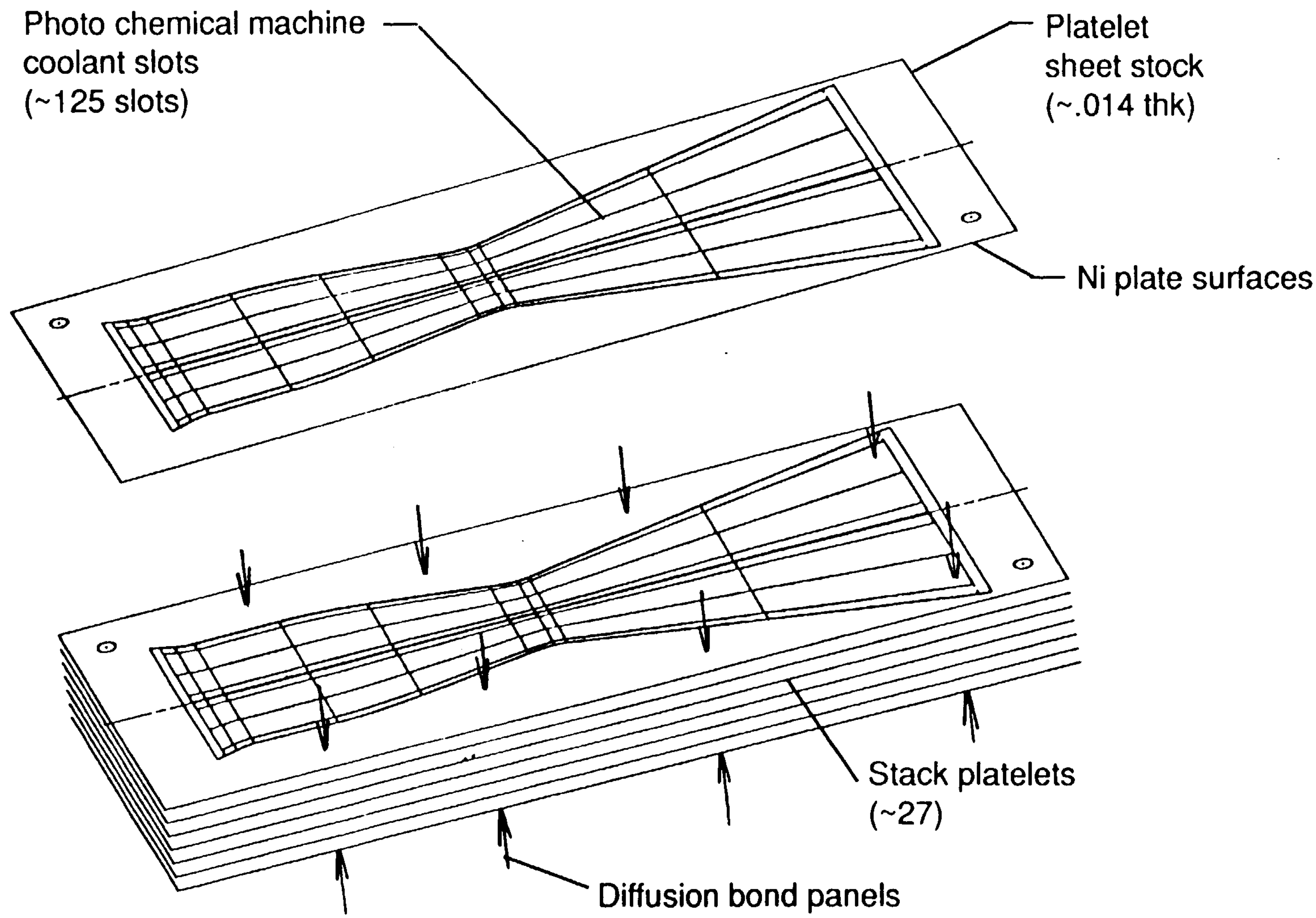
PLATELET COMBUSTION CHAMBER FABRICATION SEQUENCE



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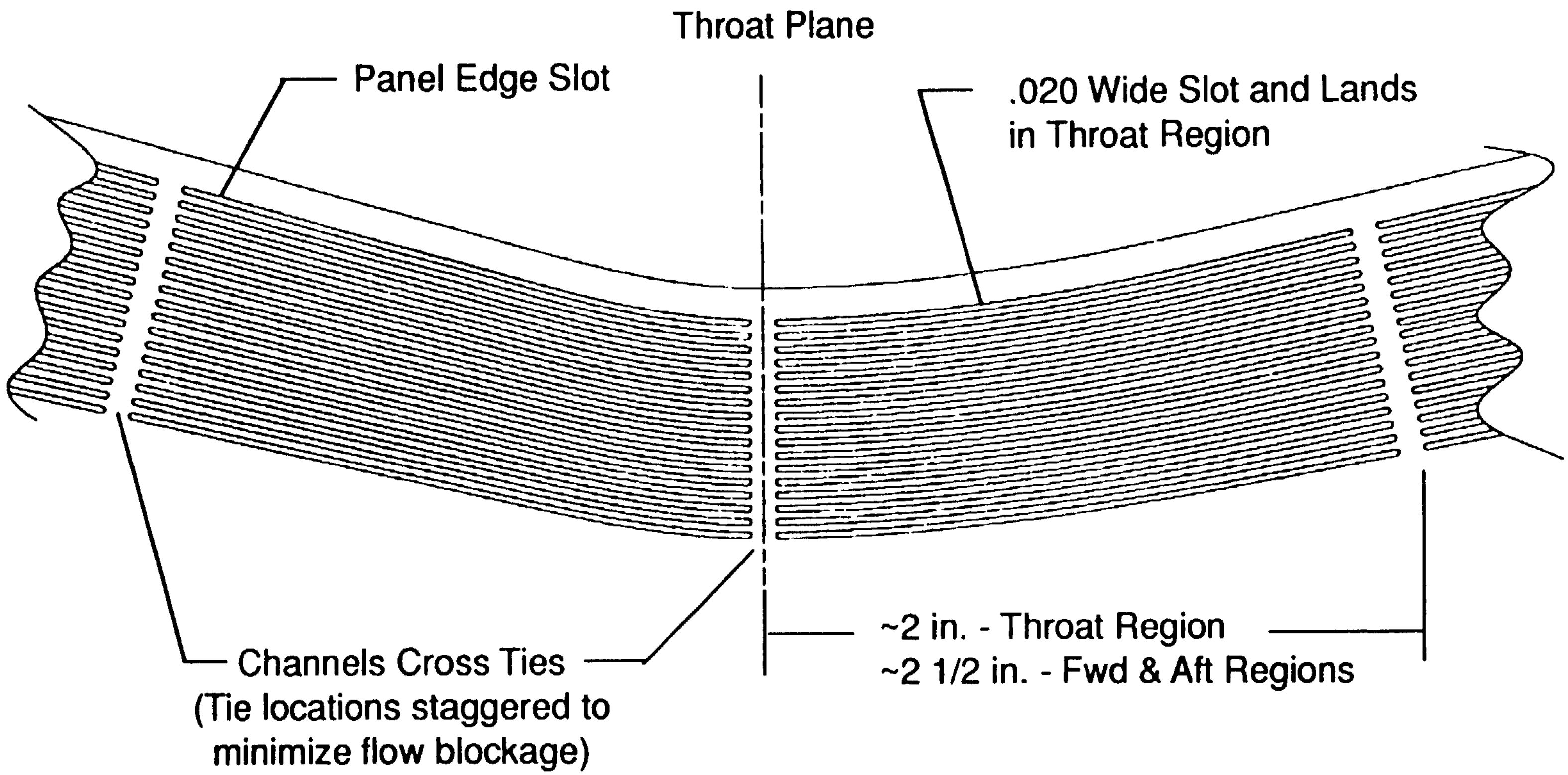
PLATELET COMBUSTION CHAMBER
Sheet Etching Pattern



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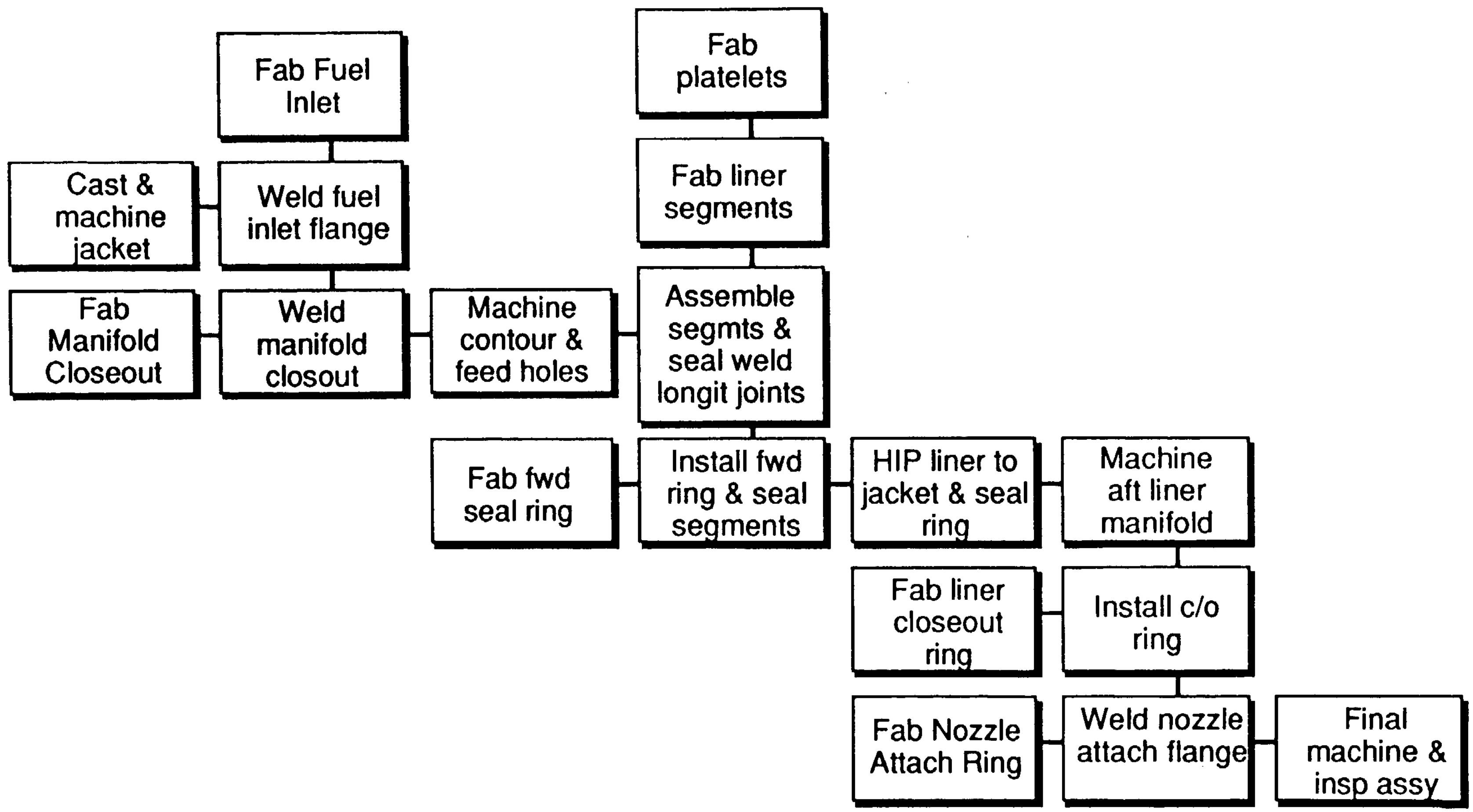
CAST JACKET/PLATELET LINER COMBUSTION CHAMBER

Fab Flow



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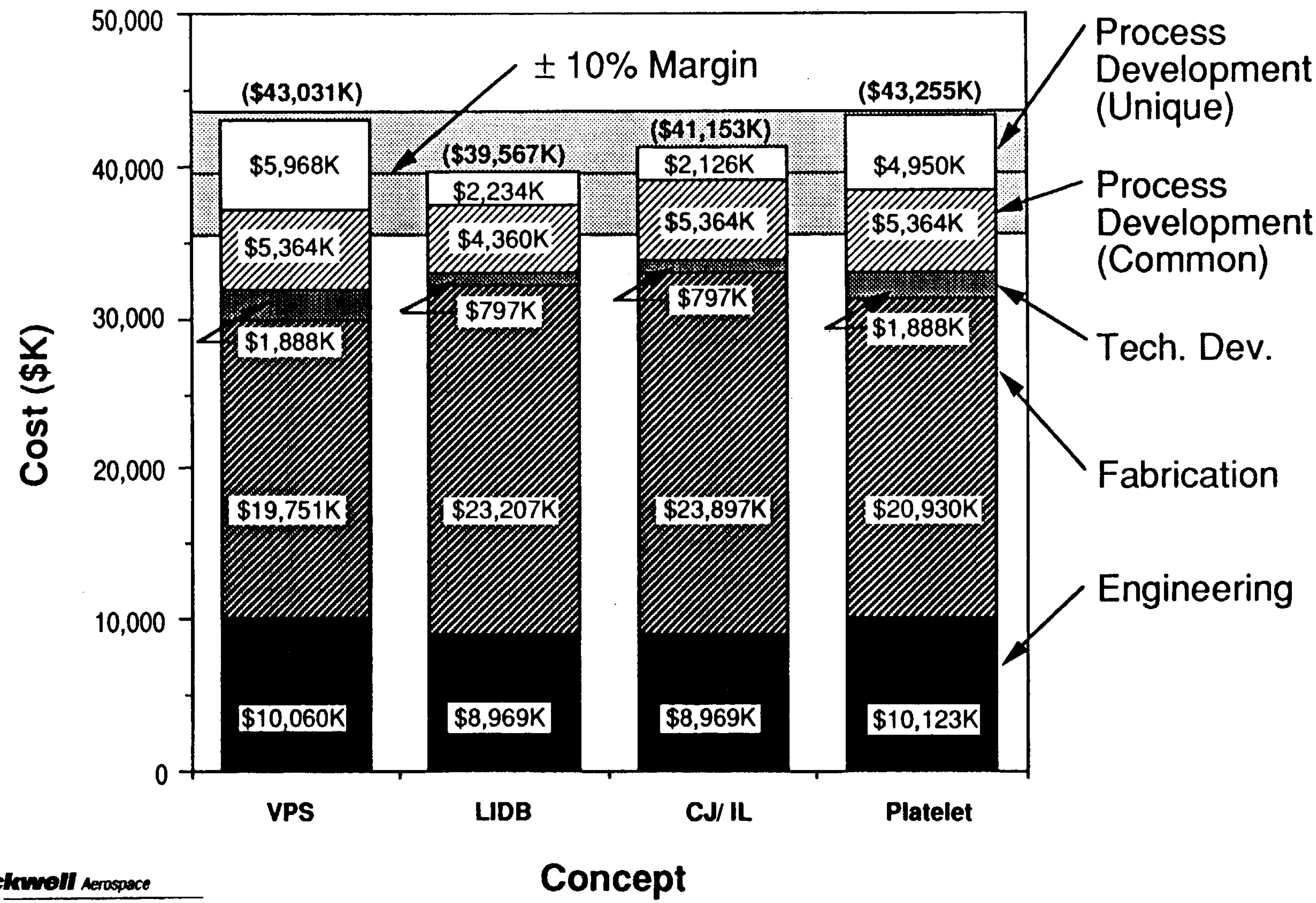
CONCEPT DEVELOPMENT COSTS (SEGMENT I ACTIVITIES)



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VPS COMBUSTION CHAMBER COST BY WBS - June 1992

WBS	ITEM DESCRIPTION	TFU			AVERAGE UNIT			NTH UNIT		
		LABOR ($)	MATERIAL ($)	TOTAL ($)	LABOR ($)	MATERIAL ($)	TOTAL ($)	LABOR ($)	MATERIAL ($)	TOTAL ($)
100	FINAL MACHINING & TEST	13,751	0	13,751	8,004	0	8,004	7,174	0	7,174
110	EB WELD NOZZLE ATTACHMENT	4,267	0	4,267	2,484	0	2,484	2,226	0	2,226
120	WELD FUEL INLET	2,993	0	2,993	1,742	0	1,742	1,561	0	1,561
130	ELECTROPLATE SEAL RING	4,657	0	4,657	2,710	0	2,710	2,429	0	2,429
140	FINISH MACHINE HOT GAS WALL	3,707	45,019	48,726	2,158	45,019	47,177	1,934	45,019	46,953
150	VPS HOT GAS WALL	14,602	14,656	29,258	8,499	14,656	23,155	7,618	14,656	22,274
160	FILL CHANNELS	19,154	8,111	27,265	11,148	8,111	19,259	9,993	8,111	18,104
170	SLOT COLD WALL	45,995	0	45,995	26,771	0	26,771	23,996	0	23,996
180	HIP COLD WALL (PURCHASED LABOR)	0	29,407	29,407	0	29,407	29,407	0	29,407	29,407
181	NARloy-Z POWDER	0	30,909	30,909	0	30,909	30,909	0	30,909	30,909
182	HIP BAG	0	29,792	29,792	0	29,792	29,792	0	29,792	29,792
190	WELD AFT MANIFOLD & MACHINE HOLES	13,477	0	13,477	7,844	0	7,844	7,031	0	7,031
200	MACHINE AFT MANIFOLD ID INSERT	7,520	9,027	16,547	4,377	9,027	13,404	3,923	9,027	12,950
210	MACHINE CC CASTING	6,748	120,092	126,840	3,927	120,092	124,020	3,520	120,092	123,613
220	FAB FUEL INLET FLANGE	992	1,881	2,873	577	1,881	2,459	517	1,881	2,399
230	MACHINE NOZZLE ATTACH FLANGE	12,352	51,327	63,679	7,189	51,327	58,516	6,444	51,327	57,771
	TOTAL HARDWARE	150,215	340,222	490,438	87,430	340,222	427,653	78,368	340,222	418,590
501	RECURRING TOOLING (% OF FAB)	20,377		20,377	11,860		11,860	10,631		10,631
502	ENGINEERING & TEST (% OF FAB)	41,381		41,381	24,085		24,085	21,589		21,589
503	Q.A./INSPECTION (% OF FAB)	41,381		41,381	24,085		24,085	21,589		21,589
504	MANUF & FACILITIES (LOE)	94,590		94,590	94,590		94,590	94,590		94,590
505	ENGINEERING & TEST (LOE)	18,298		18,298	18,298		18,298	18,298		18,298
506	Q.A. (LOE)	21,487		21,487	21,487		21,487	21,487		21,487
507	MANAGEMENT & REPRO (LOE)	4,168		4,168	4,168		4,168	4,168		4,168
508	FIXED EXPENSE	1,169		1,169	1,169		1,169	1,169		1,169
509	MATERIAL CONTROL		222	222		222	222		222	222
510	MATERIAL ADMINISTRATION		438	438		438	438		438	438
511	RECEIVING/SOURCE INSPECTION		1,457	1,457		1,457	1,457		1,457	1,457
	TOTAL SUPPORT	242,852	2,117	244,968	199,743	2,117	201,860	193,521	2,117	195,637
	TOTAL HARDWARE & SUPPORT	393,067	342,339	735,406	287,173	342,339	629,513	271,889	342,339	614,228
	TOTAL COST/PRICE	477,773	416,113	893,886	349,059	416,113	765,173	330,481	416,113	746,594

touch labor rate ($/hr)		production rate	30
support labor rate ($/hr)		procurement lot size	30
G&A + COM		production quantity	500
Fee		year-dollar reported	1,991
automation level	1	Nth unit reported	500
specification level	1	TFU touch labor hours	3,110

94LS/077-375

LIDB COMBUSTION CHAMBER COST BY WBS - June 1992

WBS	ITEM DESCRIPTION	TFU LABOR ($)	TFU MATERIAL ($)	TFU TOTAL ($)	AVERAGE UNIT LABOR ($)	AVERAGE UNIT MATERIAL ($)	AVERAGE UNIT TOTAL ($)	NTH UNIT LABOR ($)	NTH UNIT MATERIAL ($)	NTH UNIT TOTAL ($)
100		0	0	0	0	0	0	0	0	0
110	FINAL ASSEMBLY	13,751	2,410	16,162	8,004	2,410	10,414	7,174	2,410	9,584
120	WELD NOZZLE ATTACHMENT FLANGE	4,267	0	4,267	2,484	0	2,484	2,226	0	2,226
130	WELD FUEL INLET FLANGE	2,993	0	2,993	1,742	0	1,742	1,561	0	1,561
140	ED NICKEL-COBALT	62,836	5,760	68,595	36,572	5,760	42,332	32,782	5,760	38,541
150	WAX FILL & ED COPPER	67,904	1,333	69,237	39,523	1,333	40,856	35,426	1,333	36,759
160	LIDB FORWARD & AFT FLANGE	34,481	24,393	58,873	20,069	24,393	44,462	17,989	24,393	42,382
165	LIDB PRESSURE BAG	0	7,876	7,876	0	7,876	7,876	0	7,876	7,876
170	SLOT NARloy-Z LINER	40,172	0	40,172	23,381	0	23,381	20,958	0	20,958
180	MACHINE NARloy-Z LINER	8,604	49,221	57,824	5,008	49,221	54,228	4,489	49,221	53,709
190	WELD MANIFOLD CLOSEOUT	13,477	0	13,477	7,844	0	7,844	7,031	0	7,031
200	FORWARD FLANGE BRAZE ASSEMBLY	9,436	1,881	11,317	5,492	1,881	7,373	4,923	1,881	6,804
210	AFT MANIFOLD CASTING AND MACHINE	1,233	56,007	57,240	718	56,007	56,725	643	56,007	56,650
220	MACHINE AFT MANIFOLD CLOSEOUT RING	7,520	7,125	14,645	4,377	7,125	11,502	3,923	7,125	11,048
230	MACHINE FORWARD MANIFOLD FLANGE	7,591	3,360	10,951	4,418	3,360	7,778	3,960	3,360	7,320
240	MACHINE SEAL RING	1,524	1,764	3,288	887	1,764	2,651	795	1,764	2,559
250	FAB FUEL INLET	992	1,763	2,755	577	1,763	2,341	517	1,763	2,281
260	MACHINE NOZZLE ATTACHMENT FLANGE	12,352	51,137	63,489	7,189	51,137	58,326	6,444	51,137	57,581
270	ED NI-CO THRUST CONE	33,485	18,234	51,719	19,490	18,234	37,724	17,470	18,234	35,704
	TOTAL HARDWARE	322,618	232,263	554,881	187,775	232,263	420,038	168,311	232,263	400,575
501	RECURRING TOOLING (% OF FAB)	43,764		43,764	25,472		25,472	22,832		22,832
502	ENGINEERING & TEST (% OF FAB)	88,874		88,874	51,728		51,728	46,366		46,366
503	INSPECTION (% OF FAB)	88,874		88,874	51,728		51,728	46,366		46,366
504	MANUF & FACILITIES (LOE)	94,590		94,590	94,590		94,590	94,590		94,590
505	ENGINEERING & TEST (LOE)	18,298		18,298	18,298		18,298	18,298		18,298
506	Q.A.(LOE)	21,487		21,487	21,487		21,487	21,487		21,487
507	MANAGEMENT & REPRO (LOE)	4,168		4,168	4,168		4,168	4,168		4,168
508	FIXED EXPENSE	1,169		1,169	1,169		1,169	1,169		1,169
509	MATERIAL CONTROL		222	222		222	222		222	222
510	MATERIAL ADMINISTRATION		438	438		438	438		438	438
511	RECEIVING/SOURCE INSPECTION		1,457	1,457		1,457	1,457		1,457	1,457
	TOTAL SUPPORT	361,225	2,117	363,341	268,640	2,117	270,757	255,276	2,117	257,393
	TOTAL HARDWARE & SUPPORT	683,843	234,380	918,223	456,415	234,380	690,795	423,588	234,380	657,968
	TOTAL COST/PRICE	831,211	284,889	1,116,100	554,772	284,889	839,661	514,871	284,889	799,760

touch labor rate ($/hr)		production rate	30
support labor rate ($/hr)		procurement lot size	30
G&A + COM		production quantity	500
Fee		year-dollar reported	1,991
automation level	1	Nth unit reported	500
specification level	1	TFU touch labor hours	6,679

94LS/077-376

PLATELET COMBUSTION CHAMBER COST BY WBS - June 1992

WBS	ITEM DESCRIPTION	TFU LABOR ($)	TFU MATERIAL ($)	TFU TOTAL ($)	AVERAGE UNIT LABOR ($)	AVERAGE UNIT MATERIAL ($)	AVERAGE UNIT TOTAL ($)	NTH UNIT LABOR ($)	NTH UNIT MATERIAL ($)	NTH UNIT TOTAL ($)
110	FINAL MACHINING & TEST	13,593	0	13,593	7,912	0	7,912	7,092	0	7,092
120	EB WELD NOZZLE ATTACHMENT	4,267	0	4,267	2,484	0	2,484	2,226	0	2,226
130	WELD FUEL INLET	3,290	0	3,290	1,915	0	1,915	1,716	0	1,716
140	WELD AFT CLOSEOUT RING	0	0	0	0	0	0	0	0	0
150	MACHINE AFT MANIFOLD	5,549	0	5,549	3,229	0	3,229	2,895	0	2,895
160	HIP LINER TO JACKET (INCLUDED)	0	0	0	0	0	0	0	0	0
170	FORWARD SEAL RING ASSEMBLY	7,100	0	7,100	4,133	0	4,133	3,704	0	3,704
180	INSTALL LINER (INCLUDED)	0	0	0	0	0	0	0	0	0
190	BOND PLATELET SHEETS (INCLUDE	0	0	0	0	0	0	0	0	0
200	PLATELET LINER (AEROJET)	0	0	0	0	0	0	0	0	0
210	MACHINE FEED HOLES, ANNULUS	25,242	0	25,242	14,692	0	14,692	13,169	0	13,169
220	WELD AFT MANIFOLD	4,416	0	4,416	2,570	0	2,570	2,304	0	2,304
230	MACHINE CC CASTING	6,748	120,092	126,840	3,927	120,092	124,020	3,520	120,092	123,613
240	MACHINE AFT MANIFOLD INSERT	7,183	9,027	16,210	4,181	9,027	13,208	3,747	9,027	12,774
250	MACHINE SEAL RING	1,195	1,881	3,076	695	1,881	2,577	623	1,881	2,505
260	MACHINE AFT CLOSEOUT CAP RING	0	0	0	0	0	0	0	0	0
270	MACHINE NOZZLE ATTACHMENT FL	12,352	51,327	63,679	7,189	51,327	58,516	6,444	51,327	57,771
280	FABRICATE FUEL INLET FLANGE	992	1,881	2,873	577	1,881	2,459	517	1,881	2,399
	TOTAL HARDWARE	91,926	184,209	276,135	53,504	184,209	237,713	47,958	184,209	232,167
501	RECURRING TOOLING (% OF FAB)	12,470		12,470	7,258		7,258	6,506		6,506
502	ENGINEERING & TEST (% OF FAB)	25,324		25,324	14,739		14,739	13,211		13,211
503	INSPECTION (% OF FAB)	25,324		25,324	14,739		14,739	13,211		13,211
504	MANUF & FACILITIES (LOE)	94,590		94,590	94,590		94,590	94,590		94,590
505	ENGINEERING & TEST (LOE)	18,298		18,298	18,298		18,298	18,298		18,298
506	Q.A.(LOE)	21,487		21,487	21,487		21,487	21,487		21,487
507	MANAGEMENT & REPRO (LOE)	4,168		4,168	4,168		4,168	4,168		4,168
508	FIXED EXPENSE	1,169		1,169	1,169		1,169	1,169		1,169
509	MATERIAL CONTROL		222	222		222	222		222	222
510	MATERIAL ADMINISTRATION		438	438		438	438		438	438
511	RECEIVING/SOURCE INSPECTION		1,457	1,457		1,457	1,457		1,457	1,457
	TOTAL SUPPORT	202,830	2,117	204,946	176,449	2,117	178,566	172,641	2,117	174,758
	TOTAL HARDWARE & SUPPORT	294,756	186,326	481,082	229,953	186,326	416,279	220,599	186,326	406,925
	TOTAL COST/PRICE	358,276	226,479	584,755	279,508	226,479	505,987	268,138	226,479	494,618
	LINER (AEROJET)	276,109	39,482	315,591	160,705	39,482	200,187	144,047	39,482	183,529
	TOTAL	**634,385**	**265,961**	**900,346**	**440,213**	**265,961**	**706,174**	**412,186**	**265,961**	**678,147**

touch labor rate ($/hr)		production rate	30
support labor rate ($/hr)		procurement lot size	30
G&A + COM		production quantity	500
Fee		year-dollar reported	1,991
automation level	1	Nth unit reported	500
specification level	1	TFU touch labor hours	1,903

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DEVELOPMENT RISK ASSESSMENT

- **During development of the process a method of rating the risk for each step was required**
  - The rating concept is derived from Bart Huthwaite's class on "Design for Competitiveness"
  - Each risk category was ranked at one of four step levels
    - No Risk — Process is well established
    - Step — Minor tailoring of well established process
    - Stretch — Moderate extrapolation of existing technology
    - Leap — Significant technology development required
- **Detailed definitions of technical and schedule risk were produced**
- **Technical assessment of risk is independent of funding and program schedule**
- **Schedule risk covers programmatic concerns**

DEFINITIONS OF TECHNICAL RISK CATEGORIES

- **Process**

  The risk associated with the primary processes used to fabricate the combustion chamber. This risk is directly proportional, in most cases, to the development effort required.

- **Material**

  The impact of the primary processes used in fabrication upon the material properties of any part of the combustion chamber. This includes the effect of additional thermal cycles, bonding processes, diffusion of non-constitutive atoms into an alloy (thus changing the alloy's chemistry and material behavior), or any other impact upon the capability of the materials to satisfy the required design criteria, after processing steps. This impact may be either direct (i.e., VPS spray of NARloy-Z, forging, etc.) or indirect (effect of braze cycle on liner material properties).

- **Inspection**

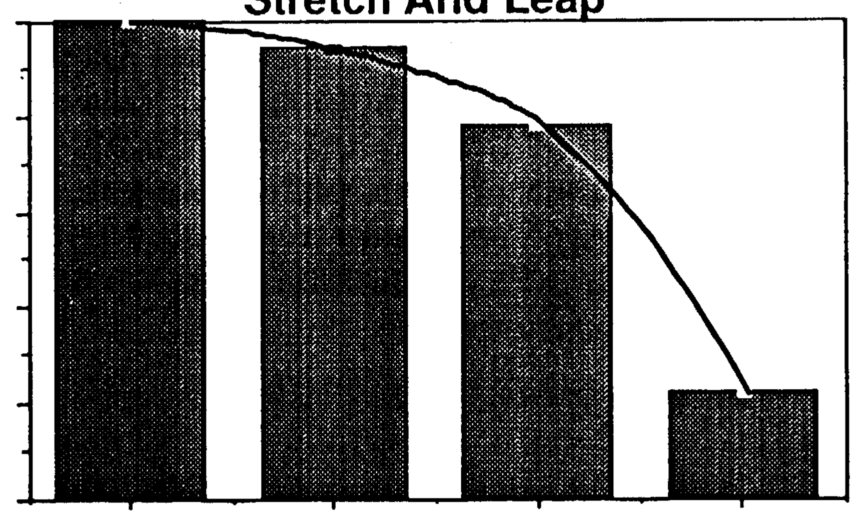
  The risk associated with the primary processes used to inspect the combustion chamber. This risk is directly proportional, in most cases, to the development effort required.

COMPARATIVE EVALUATION

- **To allow comparative evaluation numeric values were assigned to step, stretch, and leap**
  - An arbitrary value was chosen for a step
  - Stretch and leap values were calculated based on the step value

- No Risk 1.0
- Step 0.97 - Arbitrary number
- Stretch 0.89 - Equal to four steps
- Leap 0.61 - Equal four stretches

Relation Between Step, Stretch And Leap



- **Values are not percentage**

NUMERICAL ROLL-UPS

- **Technical risk (Process, material and inspection) and schedule risk are multiplied down each column to contain an over-all comparative number**

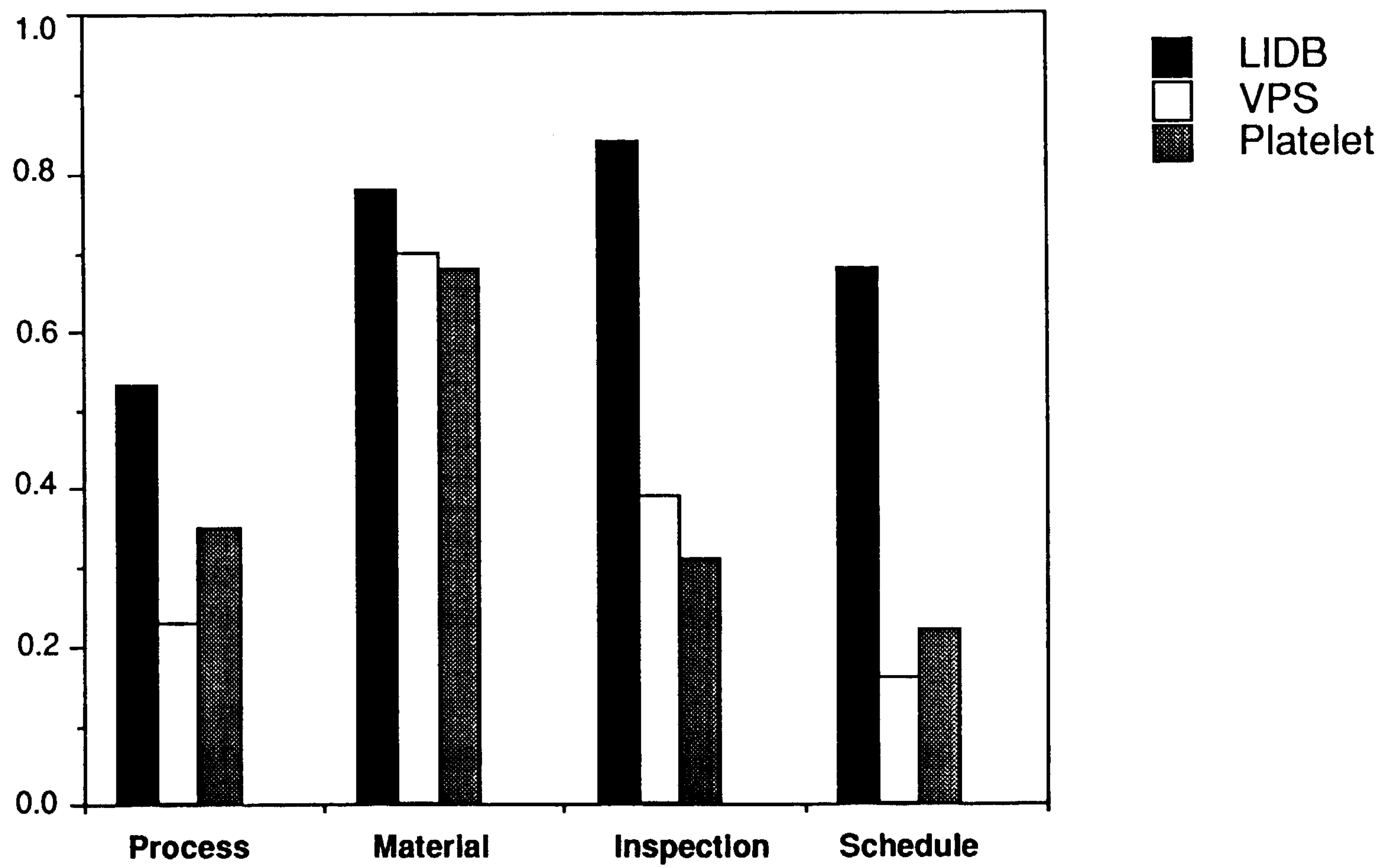
- **Related processing steps are individually multiplied to determine problem areas**

LIDB	Process	Material	Inspection	Schedule
- Au Plate Liner Ends O.D.	0.97	1.00		1.00
- Blister Test			1.00	1.00
- Cu Plate Fwd Flange & Aft Manifold	0.97	1.00		1.00
- Blister Test			1.00	1.00
- Ni Plate Fwd Flange & Aft Manifold	1.00	1.00		1.00
- Blister Test			1.00	1.00
- Braze	0.89	0.97		0.97
- Age JBK & LIDB	1.00			1.00
- Inspect LIDB Bond (Pent, UT, Proof)			0.89	0.97
- Machine	1.00			1.00
Total	0.84	0.97	0.89	0.94

- **Low values are indicative of high risk processing steps**
  - Fabrication step roll-ups lower than 0.89 were deemed "High Risk"

RELATIVE DEVELOPMENT RISK OF COMBUSTION CHAMBER CONCEPTS

(Higher Is Better)



SIGNIFICANT DEVELOPMENT RISK CONCERNS

- **LIDB**
  - Spin form of large NARloy-Z casting
  - Liner/casting LIDB bond inspection
- **VPS**
  - NARloy-Z VPS of hot wall
  - Channel filler material/processing/inspection
  - Cold wall HIP bag design
  - Hot wall machining/inspection
- **Platelet**
  - Large panel diffusion bonding
  - Laser weld sealing of panel segment joints
  - Liner/casting bond inspection
  - Large panel die forming

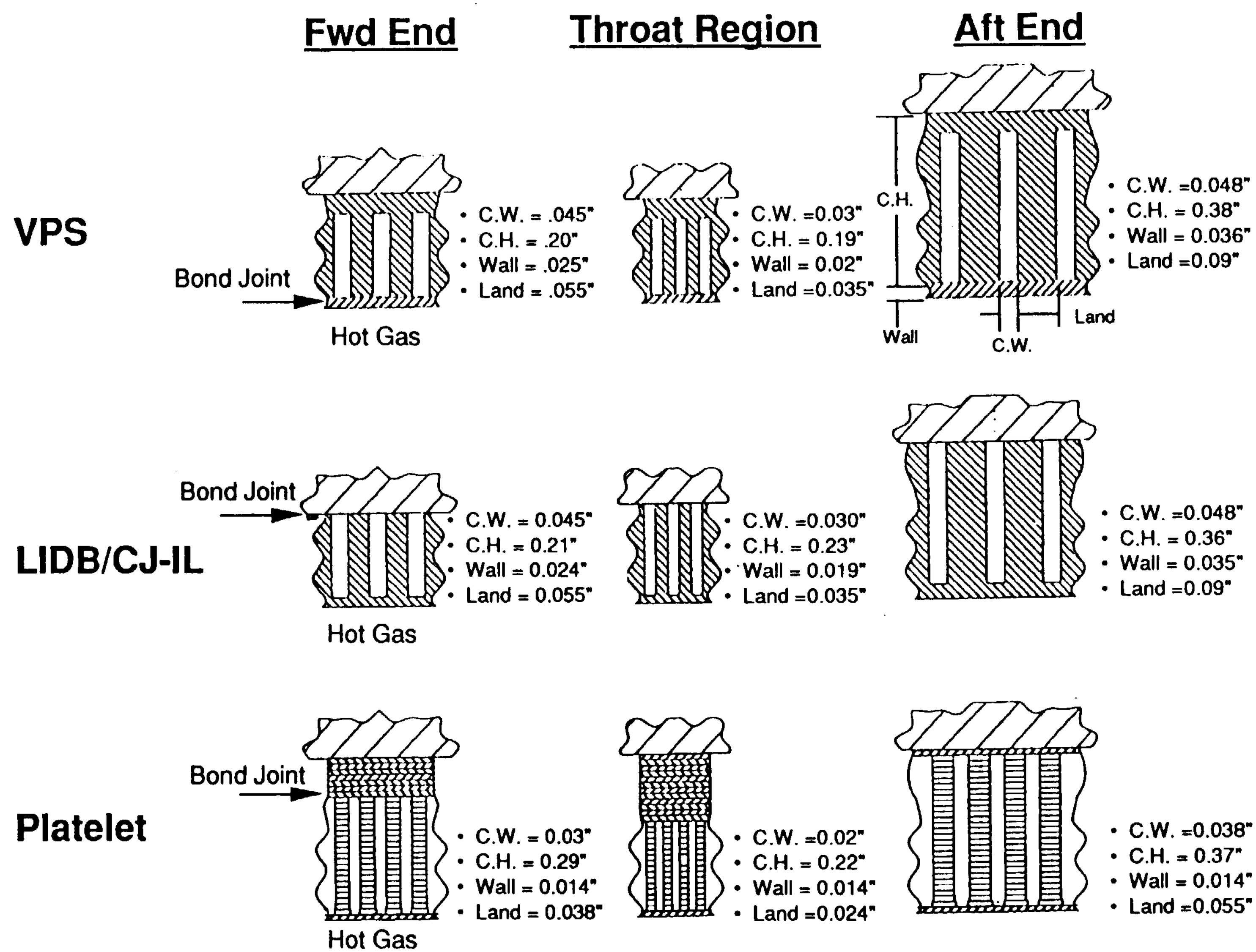
OPERTIONAL RELIABILITY
Failure Modes

- **A failure mode is a functional failure**
- **Failure modes were obtained from the combustion chamber preliminary FMEA**
  - Liner fails to obtain coolant
  - Manifold fails to contain coolant
  - Jacket or nozzle flange fail to contain pressure
  - Jacket or nozzle flange fails to transmit loads
  - Chamber to injector interface fails to contain coolant
- **All the concepts have the same failure modes**
- **All the concepts assumed to have about the same reliability**

DESIGN CONSTRAINTS

	VPS	Wrought or LIDB	Amzirc (Platelet)
• Max Temp (@ MDC + 100° streak)	1000°F (LCF)	1100°F (blanching)	1000°F (Aerojet)
• Max Hot Wall Bond Temp (@ MDC + 100°streak)	1100°F	DNA	750°F
• Max. Coolant ΔP (psi)	1098	1098	1098
• Channel Geometry			
• Min. CW/Min. LW/AR @ Tht.	.030/.030/9	.030/.030/9	.020/.020/15
• Wall Thk Tol	±.003	±.002	±.001
• Min. Wall Thk (Stress)	.015	.012	.012
• Min. Wall Thk. (Mfg)	.010	.016	No limit
• Cycle Life (min. @ MDC)	13 x 4	13 x 4	13 x 4
• Coolant Side ε (μin)	32	20	32
• Max. Q/A at nominal condition	73	73	73

COOLANT CHANNEL GEOMETRICAL CONFIGURATIONS



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THERMAL PERFORMANCE COMPARISON
June 1992

	LIDB	VPS	Platelet
• Aft End Temperature (°F)	172	189	119
• Throat Temperature (°F)	610	582	566
• Fwd End Temperature (°F)	748	720	704
• Maximum Wall Temperature (°F)	800	714	683
• ΔP (psi)	1010	1300	1120

PRELIMINARY CONCEPT COMPARISON

Updated November 1992

Selection Criteria	Rank	Chamber Configuration			Advantage
		LIDB	VPS	Platelet	
Development Cost ($M) (1)	1	37.3	44.1	40.3	LIDB
Production Cost ($K) (1)	2	861	767 (2)	699 (2)	Platelet
Development Risk	3	Low	High	High	LIDB
Operational Reliability	4	High	High	High	---
Weight (lbs)	5	1311	1492	1466	LIDB
Performance (ΔP, psid)	6	1010	1280	1140	LIDB
Cost/Perfor./Weight Vehicle Merit (3)		3.22	3.62	3.35	LIDB

Note: All values require further iteration

(1) Costs in $ 1991

(2) Further effort required to define VPS and Platelet 50% confidence costs

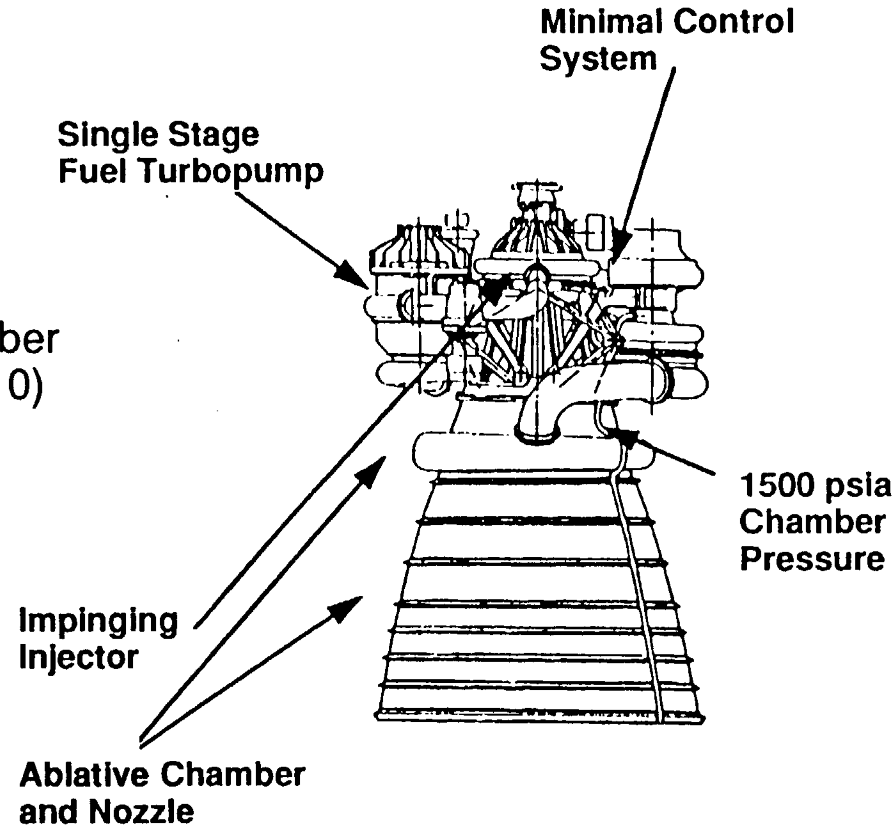
(3) = (Prod. Cost + $1300*ΔP + $800*Weight)/1,000,000
(50K payload, 580K engine sensitivities)

Rockwell Aerospace
Rocketdyne

3.2 DERIVATIVE ENGINE COMBUSTION CHAMBER CONCEPT (ABLATIVE)

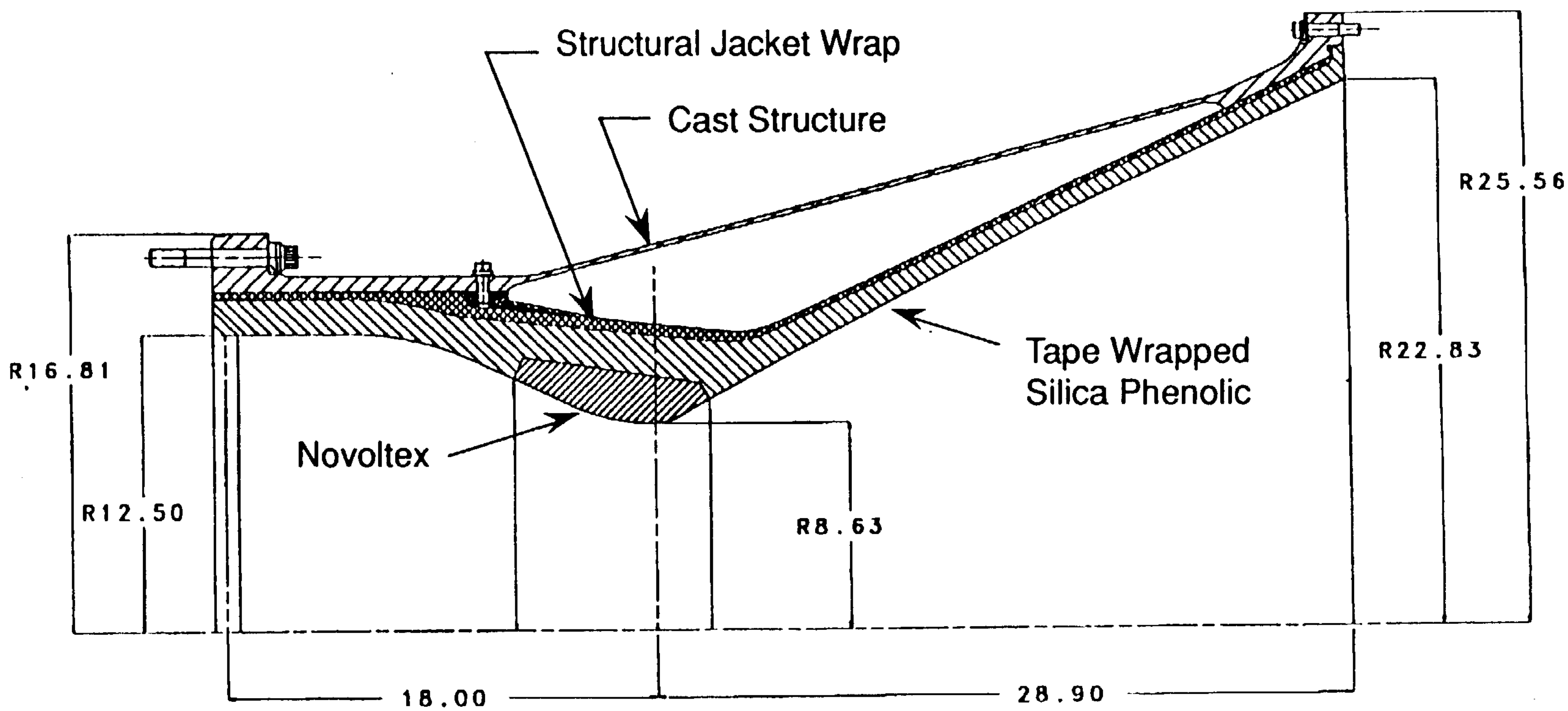
STME-130
Expendable With Ablative Chamber And Nozzle

- **Engine Attributes:**
  - $4.9M acquisition cost *
  - High mission reliability, 0.995
  - Fail safe for loss of power and chamber pressure redline (similar to STME-110)
  - Minimum prelaunch processing time
- **Additional Low Cost Features:**

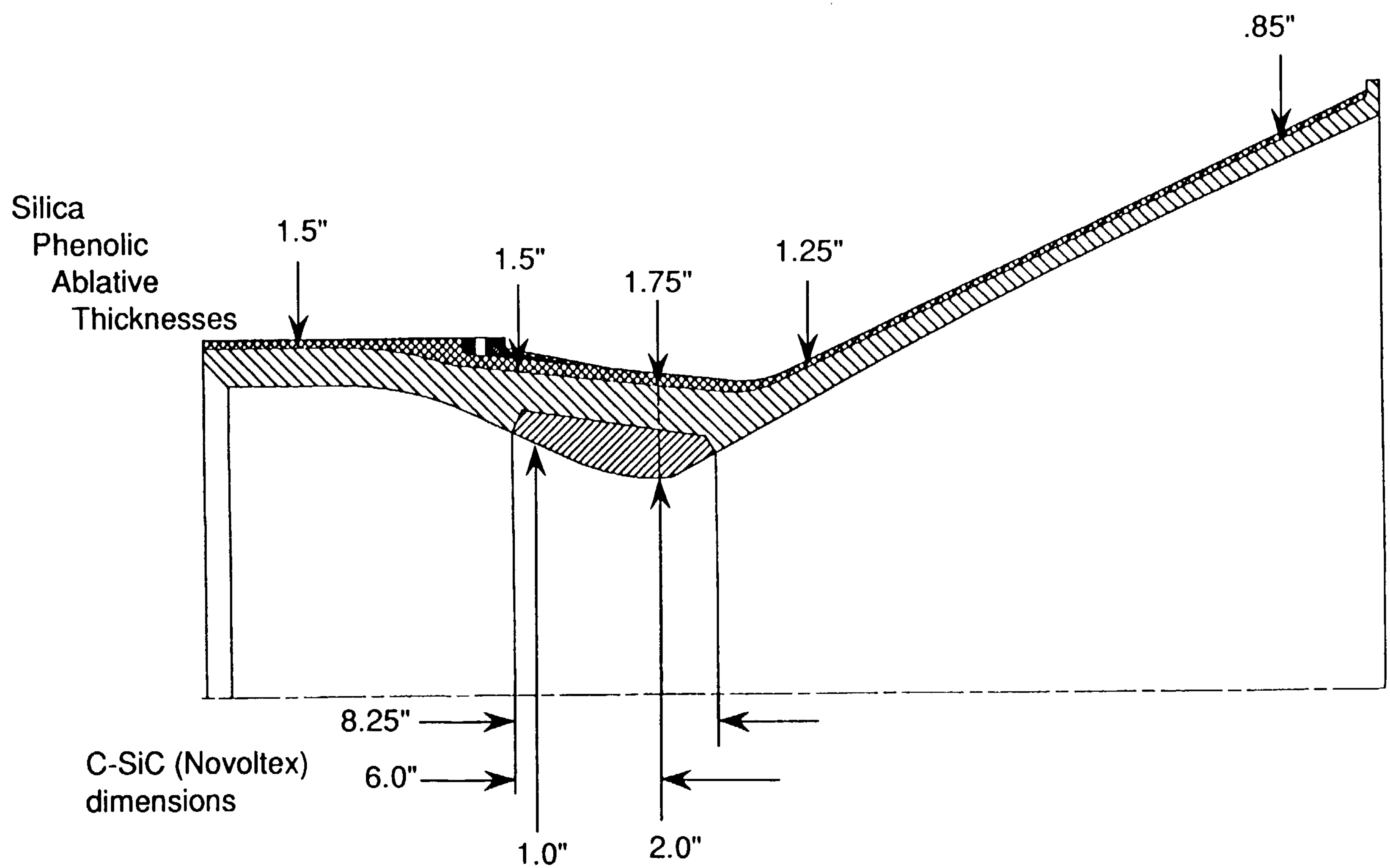


*Based on GFY91$, includes fee and FCCM/cumulative average of first 24 engines at 10 per year

STME 130
PASSIVELY COOLED COMBUSTION CHAMBER



STME 130
PASSIVELY COOLED COMBUSTION CHAMBER
Material Thicknesses



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DESIGN CRITERIA AND PROPERTIES

Parameter	Silica Phenolic	Carbon/Silica Carbide
Maximum Wall Temperature, °F	3000	3100
Maximum Bondline Temperature, °F	600	
Density, GM/ML	1.7	2.0
Conductivity, BTU/HR-FT-°F	.23	14
CTE, IN/IN °F x 10^6	4.5	1.0
Strain to Failure, %	.4	1.0
Tensile Strength, KSI	12	35
Modulus, KSI x 10^6	2.5	15

COMBUSTION CHAMBER DESIGN CHANGES

STME 100	STME 130
• Regenerative cooling/w BLC	• Boundary layer cooling
• Milled channel NARloy-Z liner	• Silica phenolic ablative liner w/ Novoltex throat insert
• LIDB attached manifold and forward flange	• No manifolds
• ED/Ni-CO channel closeout and jacket	• Carbon phenolic structural jacket overwrap
• Plated thrust structure	• Cast thrust structure and attach flanges

COMBUSTION CHAMBER PRODUCIBILITY COMPARISON

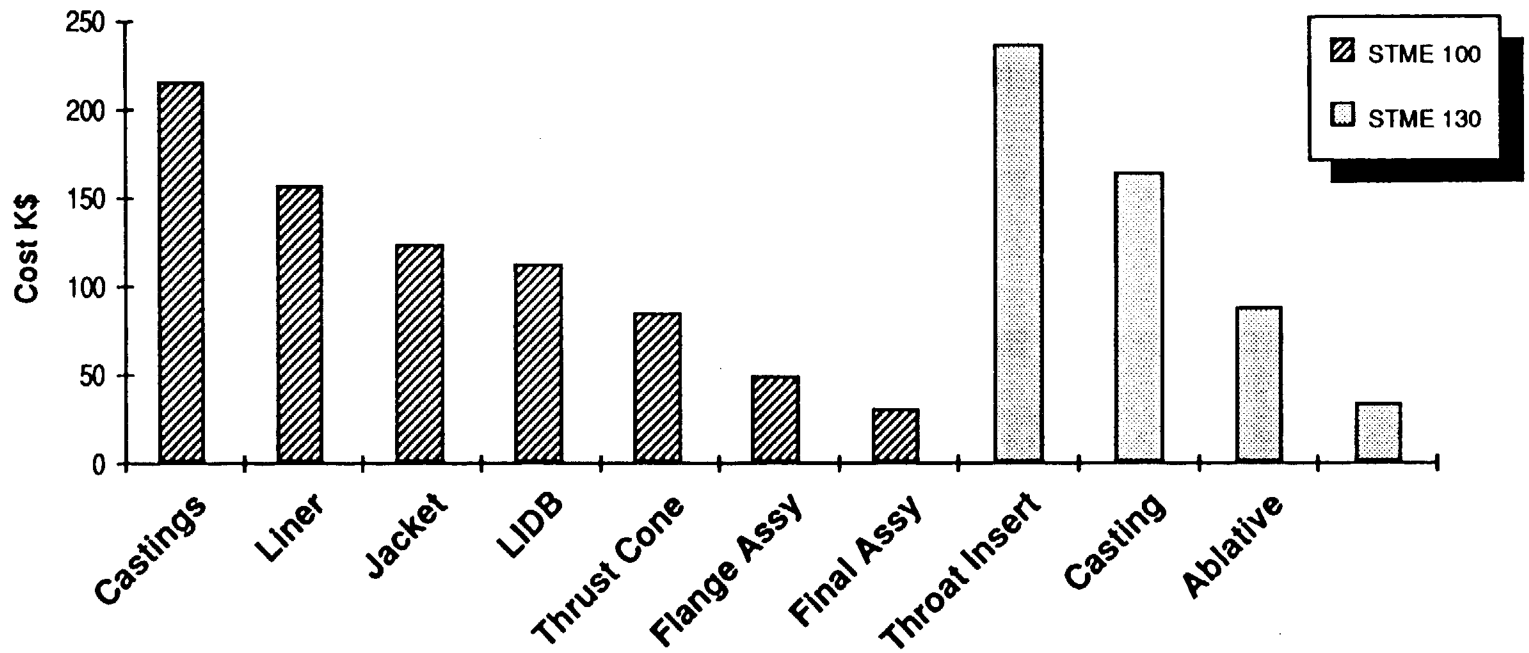
STME 100	STME 130
• Series fabrication flow	• Liner and thrust structure parallel fabrication flow
• Precision machining of liner coolant channels and mating surfaces to manifold and forward flange	• Much simpler to machine ablative, refractory throat, and thrust structure
• LIDB furnace cycle	• Autoclave cure cycle
• Multiple plating cycles	• No plating

COMBUSTION CHAMBER FAILURE MODE COMPARISON

STME 100	STME 130
• Liner fails to contain coolant	• Jacket fails to contain pressure
• Manifold fails to contain coolant	• Loss of liner due to bondline over temp
• Jacket fails to contain pressure	• Loss of throat insert
• Jacket fails to transmit loads	• Jacket structure fails to transmit loads
• Failure of coolant or hot gas seals	• Failure of hot gas seals

STME 130
COMBUSTION CHAMBER COST COMPARISON

STME 100 total = $772K
STME 130 total = $552K



COMBUSTION CHAMBER WEIGHT COMPARISON

STME 100 weight = 1345 lbs
STME 130 weight = 1386 lbs